PB88-181698

Air Pollution Exposure Systems and Experimental Protocols. Volume 2 Description of Facilities

(U.S.) Corvallis Environmental Research Lab., OR

Sep 87

U.S. Department of Commerce
National Technical Information Service
NTIS

United States
Environmental Protection
Agency

Environmental Research
Laboratory
Corvallis OR 97333

EPA/600/3-87/037b
September 1987

PB88-181698

Research and Development

EPA

Air Pollution Exposure Systems and Experimental Protocols

Volume 2: Description of Facilities

REPRODUCED BY
U.S. DEPARTMENT OF COMMERCE
NATIONAL TECHNICAL
INFORMATION SERVICE
SPRINGFIELD, VA. 22161

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA/600/3-87/037b	**2.**	**3. RECIPIENT'S ACCESSION NO.** PB88-181698
4. TITLE AND SUBTITLE AIR POLLUTION EXPOSURE SYSTEMS AND EXPERIMENTAL PROTOCOLS--Volume 2: Description of Facilities		**5. REPORT DATE**
		6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) W.E. Hogsett[1], D.M. Olszyk[2], D.P. Ormrod[3], G.E. Taylor [4], and D. T. Tingey [1]		**8. PERFORMING ORGANIZATION REPORT NO.**
9. PERFORMING ORGANIZATION NAME AND ADDRESS [1]EPA-Corvallis, OR; [2] U of CA, Riverside, CA, [3] U of Guelf, Ontario, Canada, and [4] Oakridge Nat'l Lab, Oakridge, TN.		**10. PROGRAM ELEMENT NO.**
		11. CONTRACT/GRANT NO.
12. SPONSORING AGENCY NAME AND ADDRESS US Environmental Protection Agency Environmental Research Laboratory 200 SW 35th Street Corvallis, OR 97333		**13. TYPE OF REPORT AND PERIOD COVERED** Published Report
		14. SPONSORING AGENCY CODE EPA/600/2

15. SUPPLEMENTARY NOTES
International Workshop on Standardization of Exposure Systems and Protocol, Corvallis, OR January 27-28, 1986

16. ABSTRACT

A first step in the process of determining if, and to what level, standardization of exposure systems and protocols should be recommended to the Forest Response Research Program is the integration of current knowledge of exposure facilities, experimental protocols for exposure, and characterization of ambient air quality as it relates to exposure protocol. This document provides both descriptions and evaluations of existing dry and wet deposition exposure facilities, monitoring equipment, and micro-environmental sampling.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group

18. DISTRIBUTION STATEMENT Release to Public	**19. SECURITY CLASS** *(This Report)* Unclassified	**21. NO. OF PAGES** 347
	20. SECURITY CLASS *(This page)* Unclassified	**22. PRICE** A15 32.95

EPA 600/3-87/037b
September 1987

AIR POLLUTION EXPOSURE SYSTEMS AND EXPERIMENTAL PROTOCOLS:
VOLUME 2: DESCRIPTION OF FACILITIES

Appendices

William E. Hogsett
US EPA Environmental Research Laboratory
200 SW 35th Street
Corvallis, OR 97333

David Olszyk
Statewide Air Pollution Research Center
University of California
Riverside, CA 92521

Douglas P. Ormrod
Department of Horticultural Sciences
University of Guelph
Guelph, Ontario N1G 2W1
Canada

George E. Taylor, Jr.
Environmental Sciences
Oak Ridge National Laboratory
P. O. Box X
Oak Ridge, TN 37830

David T. Tingey
US EPA Environmental Research Laboratory
200 SW 35th Street
Corvallis, OR 97333

ENVIRONMENTAL RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
CORVALLIS, OREGON 97333

DISCLAIMER

The information in this document has been funded wholly by the United States Environmental Protection Agency. It has been subjected to the Agency peer and administrative review, and it has been approved for publication as an EPA document. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

Table of Contents

Volume II. Description of Facilities

I. Appendices

- A. Descriptions of Facilities and Performance Evaluations -- Plume Systems for Gaseous Dry Deposition Research
- B. Descriptions of Facilities and Performance Evaluations -- Air Exclusion Systems for Gaseous Dry Deposition Research
- C. Descriptions of Facilities and Performance Evaluations -- Outdoor Chambers for Gaseous Dry Deposition Research
- D. Descriptions of Facilities and Performance Evaluations -- Outdoor Chamber for Gaseous Dry and Wet Deposition Research
- E. Descriptions of Facilities and Performance Evaluations -- Indoor Chambers for Gaseous Dry Deposition Research
  - I. Chambers for Laboratory Use
  - II. Chambers for Greenhouse Use
  - III. Chambers for Laboratory and Greenhouse Use
- F. Descriptions of Facilities and Performance Evaluations -- Systems for Rainfall Simulation Research
  - I. Indoors
  - II. Outdoors
    - A. Non-Chambered Systems
    - B. Chambered Systems
    - C. Automated Exclusion Systems
- G. Descriptions of Facilities and Performance Evaluations -- Systems for Aerosol/Mist Simulation Research
  - I. Indoors
  - II. Outdoors
- H. Descriptions of Facilities and Performance Evaluations -- Systems for Dust and Particulate Exposure Research
- I. Supplementary Reports: Some Basic Exposure Techniques

J. Supplementary Reports: Recommended Environmental Monitoring Protocol -- Controlled Environment Guidelines

K. Supplementary Reports: Suggested Measurements and Reporting Characteristics of Dry Deposition Gaseous Exposure Systems

L. Supplementary Reports: Air Quality Data Bases

M. Supplementary Reports: General Trends in Dry Deposition

II. References

APPENDIX A

Descriptions of Facilities and Performance Evaluations -- Plume Systems for Gaseous Dry Deposition Research

Publication: de Cormis, L., J. Bonte, and A. Tisne. 1975. Technique experimentale permenant l'etude de l'incidence sur la vegetation d'une pollution par le dioxyde de soufre appliquee en permanence et a dose subnecotique. Pollut. Atmos. 66:103-107.

Location: INRA Station d'Etude de la Pollution Atmospherique (INRA), France

Summary: A field exposure facility is described which consists of an array of vertical tubes positioned across a 2000 m^2 rectangular plot and used to expose small trees to sulfur dixoide.

1. Plots

The exposure plot is approximately 32 x 64 m with trees planted every 4.5 m.

2. Hardware

a. Emitters

The emitters are 2.75 m high PVC tubes located on a grid every 4.5 m across the plot. Sulfur dioxide is released from holes located 0.5 to 2.75 m along the tubes.

b. Pollutant Dispensing and Monitoring

Sulfur dioxide is dispensed from gas tanks to the emitters via solenoids and a rotameter. There is an automatic shutoff system to terminate the exposure if SO_2 becomes too high.

c. Environmental Control and Monitoring

Wind speed, air temperature, and rainfall are measured during the exposures.

d. Data Aquisition

Recorders.

3. Performance Evaluation

a. Pollutant Uniformity

Sulfur dioxide concentrations vary by 25% vertically between 0.5 and 2.5 m in the plot. Horizontal variability is approximately 240%. Temporal variability is approximately 100%, but varying with ambient wind speed.

b. Pollutant Control and Maintenance

The exposure system provides for relatively uniform exposure conditions, especially vertically in the small tree canopy. However, due to a single routine air sampling point it is difficult to assign exposure doses to particular trees.

See original article for diagram of system (reprint permission not obtained).

Publication: Greenwood, P., A. Greenhalgh, C. Baker, and M. Unsworth. 1982. A computer controlled system for exposing field crops to gaseous air pollutants. Atmos. Environ. 16:2261-2266.

Additional Publication: Baker, C. K., M. H. Unsworth, and P. Greenwood. 1982. Leaf injury on wheat plants exposed in the field in winter to SO_2. Nature 299:149-151.

Location: University of Nottingham, Nottingham, England

Summary: A facility is described for exposing grasses to SO_2 using a square computer-controlled plume system. The pollutant is released from the four sides independently, depending on wind direction.

1. Plots

The exposure plot is a 2-m square, bounded by emitters.

2. Hardware

a. Emitters

The emitters are 20-m long PVC tubes with 0.0024-m diameter holes every 1.0 m along the length. The tubes are positioned 0.2 m above the plant canopy.

b. Pollutant Dispensing and Monitoring

Sulfur dioxide is delivered from a heated tank to the pipes via a gas regulator, flow controller, rotameter, and solenoid. The SO_2 enters a chamber at the base of the emitter tubes where the incoming SO_2 is mixed with ambient air via a small fan. Excess pressure is maintained in the tube at all times to avoid blockage of the release holes. Sulfur dioxide concentrations are monitored sequentially in five positions over the plot with solenoids and a flame photometric analyzer. Sulfur dioxide is not released if wind speed is less than 1.0 m s^{-1}.

c. Environmental Control and Monitoring

Wind speed and direction are monitored continuously by computer and the determined values used to control pollutant dispensing.

d. Data Aquisition

All pollutant dispensing, monitoring, and data storage are computer controlled.

3. Performance Evaluation

a. Pollutant Uniformity

Sulfur dioxide concentrations vary by approximately 100% horizontally across the plot on a growing season basis. The average hourly concentration over an experiment varies by 20%. The central area of the plot has a more uniform SO_2 concentration and could be used to determine plant response to a more uniform SO_2 exposure.

b. Pollutant Control and Maintenance

The exposure system allows for long-term controlled exposures of plants to SO_2 under ambient environmental conditions. The good relationship between observed and theoretical pollutant concentrations with specified emission rates and wind speeds makes it possible to model SO_2 exposure to plants distant from sampling points. Thus, the system can provide not only a relatively uniform exposure for some plants, but also a gradient of exposures if particular areas of the grid are considered.

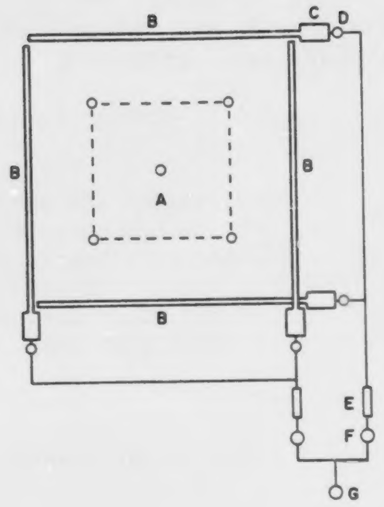


Figure A-1. Schematic diagram of computer-controlled plume system. A. Plant treatment area with "O" symbols identifying air sample points; B. emitters; C. mixing chamber; D. solenoid for controlling SO_2 release; E. flowmeter; F. flow controlled; G. SO_2 gas regulator (reprinted from Greenwood _et al_., 1982, with permission of Pergamon Press).

Publication: Lee J. J., and R. A. Lewis. 1976. Field experimental component. pp. 95-101 In: R. A. Lewis and A. S. Lefohn (eds.). The Bioenvironmental Impact of a Coal Fired Power Plant. First Interim Report Colstrip, Montana -- December 1974. U.S. Environmetal Protection Agency, Corvallis, Oregon. EPA-600/3-76-002.

Additional Publications: Lee, J. J., R. A. Lewis, and D. E. Body. 1975. A field experimental system for the evaluation of the bioenvironmental effect of sulfur dioxide. In: D. Wilson and F. Clark (eds.). Proceedings of the Fort Union Coal Field Symposium. Volume 5, pp. 608-620. Montana Academy of Science. Billings, Montana.

Preston, E. M., and J. J. Lee. 1982. Design and performance of a field exposure system for evaluation of the ecological effects of SO_2 on native grasslands. Environ. Monit. Assess. 1:213-228.

Laurenroth, W. K., D. G. Milchunas, and J. L. Dodd. 1983. Response of a grassland to sulfur dioxide and nitrogen additions under controlled SO_2 exposure. Environ. Exp. Bot. 23:339-346.

Location: U.S. Environmental Protection Agency, Colstrip Project, Colstrip, Montana

Summary: A plume system was designed, tested and used for exposures of native grasses to SO_2 in the field. The system consists of an array of emitter tubes positioned over the plant canopy. Exposures are continuous over the growing season. The system provides for controlled-exposures with variability in concentration such as may occur during SO_2 fumigation episodes from coal-fired electrical generating stations.

1. Plots

The plots are 85 x 73 m with a plant growing area of 1891 m^2.

2. Hardware

a. Emitters

The emitters are 0.0254-m diameter aluminum pipes 0.75 m above the ground. Three tubes are 85 m long, and two are 73 m long; additional 14-m length tubes are placed at right angles every 24 m. The holes are 0.008 m in diameter and located every 3.1 m along the length.

b. Pollutant Dispensing and Monitoring

Sulfur dioxide is dispensed from a heated tank of SO_2 via a valve and compressor, and is monitored with a flame photometric analyzer. Sulfur dioxide is measured in several plots with a time-sharing device.

c. Data Aquisition

Recorder.

d. Environmental Control and Monitoring

Not described.

3. Performance Evaluation

a. Pollutant Uniformity

Sulfur dioxide concentrations vary by up to 300% across plots. Sulfur dioxide concentrations are highest near the tubes on days with low wind speeds. Sulfur dioxide concentrations within plots vary by up to 20 times over the growing season. The source of this variation is most likely wind speed.

b. Pollutant Control and Maintenance

Pollutant control is electromechanical via an automatic shutoff at a specified pollutant concentration. Continuous use of the system with all wind speeds and directions results in the large horizontal and temporal variability.

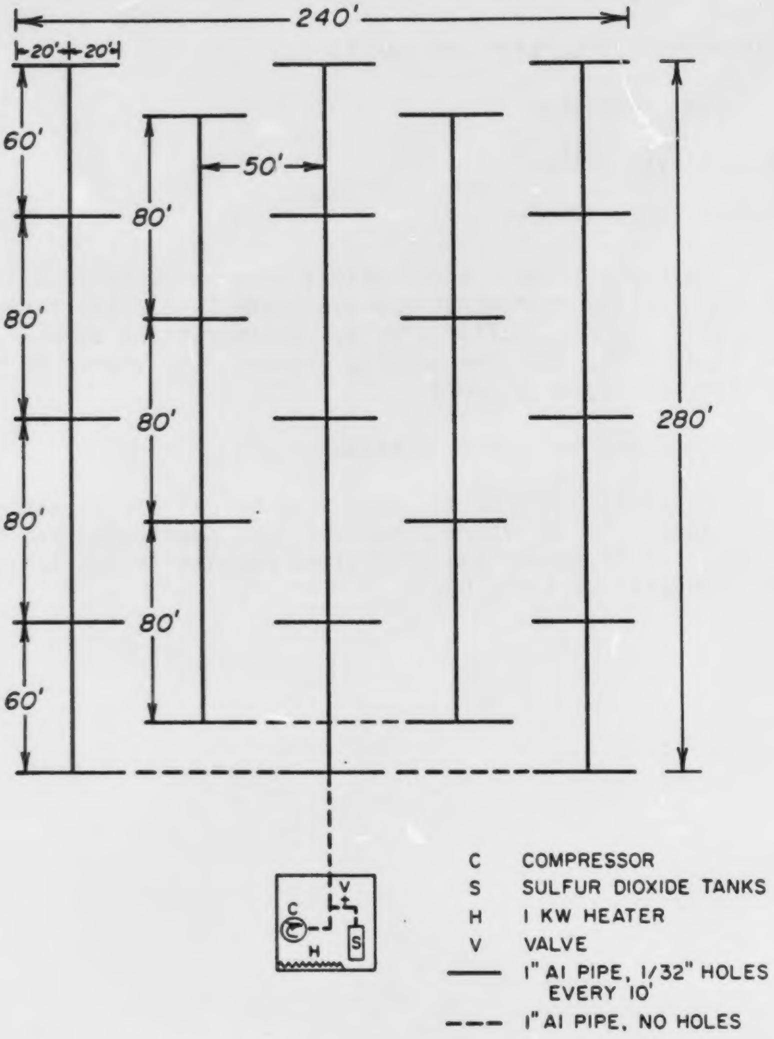


Figure A-2. Schematic diagram of plot layout for grid plume system (Zonal Air Pollution System) (Lee and Lewis, 1976).

Publication: McLeod, A. R., J. E. Fackrell, and K. Alexander. 1985. Open-air fumigation of field crops: criteria and design for a new experimental system. Atmos. Environ. 19:1639-1649.

Additional Publication: McLeod, A. R., K. Alexander, and P. Hatcher. 1983. A Prototype System for Open-Air Fumigation of Agricultural Crops. 2: Construction and Description. Central Electricity Generating Board. Technology Planning and Research Division. Report TPRD/L/2475/N83. Leatherhead, United Kingdom.

Location: Central Electricity Research Laboratories, Leatherhead, England

Summary: A plume exposure system was designed, tested, and used for exposure of grasses to air pollutants in the field under variable wind direction conditions. Design is by computer simulation to provide the best pollutant dispersion. The system is circular with an array of emitters within the center. Pollutant release is determined by a microcomputer to follow predetermined episode patterns.

1. Plots

The exposure plots are 27-m diameter circles. Sampling areas within the plots are 9-m diameter circles, resulting in 64 m^2 sampling areas.

2. Hardware

a. Emitters

The PVC pollutant emitters consist of an outside circle 27 m in diameter, with internal emitters located on a 3-m grid across the circle. The circle emits SO_2 at 0.5 m above the ground, and the internal tubes at 1.5 m above the ground. The circular tube releases SO_2 through 0.0022-m diameter holes every 3.0 m around the perimeter, and the vertical tubes release SO_2 from 0.0026-m diameter holes at the top.

b. Pollutant Dispensing and Monitoring

Sulfur dioxide is obtained from heated tanks via a computer-controlled system of solenoids and mass flow controllers. Sulfur dioxide is monitored with flame photometric analyzer, with samples sequentially obtained from different sampling points and plots. Nitrogen dioxide is measured at the plots with chemiluminescent analyzers and O_3 with an ultraviolet analyzer.

c. Environmental Control and Monitoring

The environment is not controlled with this field system. Environmental conditions during the exposure are measured, including wind speed and direction.

d. Data Acquisiton

All data acquisition was via a microcomputer system.

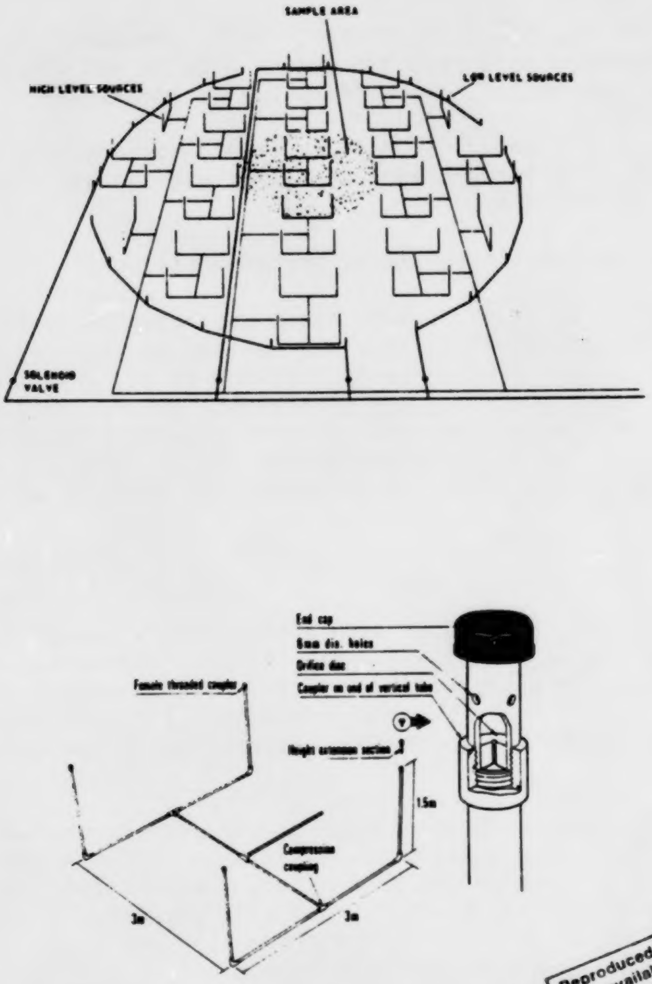
3. Performance Evaluation

a. Pollutant Uniformity

Sulfur dioxide concentrations vary vertically by > 40% between 1.4 m and the ground, < 7% across the plots, and < 10% over time within a plot.

b. Pollutant Control and Maintenance

The system provides for uniform exposure of plants to SO_2 within the sampling area. The computer control system allows for episodic exposure treatments patterned after ambient exposures. The facility is flexible for exposures with other pollutants in addition to SO_2.



Reproduced from best available copy.

Figure A-3. Schematic diagram of encircling plume system (top), and closeup of emitter head (bottom) (reprinted from McLeod _et_ _al_., 1985, with permission of Pergamon Press).

Publication: Miller, J. E., D. G. Sprugel, H. J. Smith, and P. B. Xerikos. 1980. Open-air fumigation system for investigation of sulfur dioxide effects on crops. Phytopathology 70:1124-1128.

Additional Publications: Miller, J. E., W. Prepejchal, and H. J. Smith. 1981. Relative sensitivity of field corn hybrids to ozone: a field study. Report No. ANL-81-85-III. Argonne National Laboratory, Illinois. pp. 30-36.

Irving, P. M., and J. E. Miller. 1981. Productivity of field-grown soybeans exposed to acid rain and sulfur dioxide and nitrogen dioxide alone and in combination. J. Environ. Qual. 10:473-478.

Irving, P. M., and J. E. Miller. 1984. Synergistic effect on field-grown soybeans from combinations of sulfur dioxide and nitrogen dioxide. Can. J. Bot. 62:840-846.

Location: Argonne National Laboratory, Argonne, Illinois

Summary: A modified Lee *et al.* (1975) plume was extensively tested by Argonne National Laboratory staff to simulate fumigation episodes from coal-fired power plants on agricultural crops. Miller *et al.* (1980) developed a simpler one- to five-pipe system to evaluate the response of soybeans to SO_2 alone or in combination with nitrogen dioxide (Irving and Miller, 1984), or acidic rain (Irving and Miller, 1981). The system also has been used by Miller *et al.* (1981) to determine the response of corn hybrids to O_3 exposure.

1. Plots

The plots are rectangular with approximately 783 m^2 in the exposure area and 24 m^2 in each sampling area. For SO_2 exposures, soybeans are planted in rows 1 m apart parallel to the release pipes. Plant responses are based on plants from four approximately 6.1 m wide x 5 m long subplots. Two subplots are located on either side of the central release pipe.

For O_3 exposures, the corn hybrids are planted in rows perpendicular to the O_3 release pipe. There are seven rows 0.76 m apart with 0.15 m between plants in each of the 16.2 m long x approximately 4 m wide plots. The hybrids are planted in single rows with seven hybrids per plot. Each plot is a sub-block of four replicate blocks. The plots are separated and surrounded by areas planted with seed from all 14 hybrids to ensure good density of pollen for all hybrids. Each sub-block has a 5.2-m long ambient control section to the south of the O_3 release pipe, and an 11-m long exposure section to the north of the pipe.

2. Hardware

a. Emitters

For SO_2, individual systems are smaller than the Colstrip plume system (Lee and Lewis, 1976) and the pipes are arranged in parallel to more easily fumigate row crops (Miller et al., 1980). As designed in 1977, the system consists of five 29-m sections of release pipe extending at 6.7-m intervals from one side of a 27-m long delivery pipe. The release pipes are parallel to the prevailing southerly winds, encompassing a 29 m wide by 27 m long exposure plot. Holes 0.0008-m in diameter are drilled at 0.76-m intervals on alternating sides of the release pipes horizontal to the ground. The pipe is 0.0254-m inside diameter, threaded-schedule 40 aluminum with aluminum couplings and elbows. Each system is attached to metal fence posts, and continually raised during the growing season to maintain the tubes 0.30 m above the soybean canopy. Corresponding control plots are located 10 m west of each plume. Three complete systems are located at least 40 m apart in a 4-hectare soybean field. In 1978 only the three southernmost sections of pipe were retained with the holes drilled only on their north sides. There were five complete systems located across the field. In both years of operation, each plume was assigned a different target SO_2 concentration.

The system was further adapted for O_3 exposures of 14 hybrids of field corn (Miller et al., 1981). The plume consists of a single gas release pipe of 0.025-m diameter aluminum installed in a field perpendicular to the prevailing southerly winds. The release pipe is 95-m long with 0.0008-m diameter holes at 0.61-m intervals. Ozone is produced from liquid oxygen with an OREC Model O3DV-AR O_3 generator. The O_3 is mixed with ambient air in a delivery pipe with the force for release provided by a Dietz Model SV-80 ring compressor. The O_3-air mixture enters midway along the release pipe to minimize the pressure differential along the pipe. Ozone is sampled at six points, three times each at distances of 1.8, 5.5, and 9.1 m from the pipe in two locations. Ozone concentrations at locations between sampling points are estimated from curves generated from the sampling point data. Ozone concentrations at the six points are determined through a time-sharing system, and measured with a Dasibi Model 1003AH O_3 analyzer.

b. Pollutant Dispensing and Monitoring

Sulfur dioxide is obtained from anhydrous tank SO_2 and introduced into the air stream via a pressure regulator and solenoid valve, followed by adjustable rotameters. The solenoid is operated manually whenever meteorological conditions are appropriate for exposures. In 1977, plants were exposed between 0900 and 1600 only when winds were southerly or northerly; in 1978, only when winds were southerly. Exposures have not been conducted when dew is present on leaf surfaces or in case of rain. Sulfur dioxide is monitored in the plots sequentially from sampling points via a timer-controlled electrical sequencer in conjunction with three-way solenoid valves. ThermoElectron Model 43, Meloy S160A, and Meloy S285A SO_2 analyzers are used. Sulfur dioxide data are processed manually.

c. Environmental Control and Monitoring

The system is used with an acidic rain dispensing system for some studies. Wind speed and direction are monitored during the exposures, however, no information is given concerning the frequency of wind measurements or monitoring of other environmental conditions.

d. Data Acquisition

Not described.

3. Performance Evaluation

a. Pollutant Uniformity

There is a 34% decrease in SO_2 concentration between the top of the plant canopy and soil. Concentrations of SO_2 vary by 5 to 10% horizontally across the plots. Over the course of a number of exposures, hourly-average SO_2 concentrations vary approximately 50%. There is a 10 to 20% difference in average concentrations between replicate systems. In 1978 there were 18 exposures between 19 July and 27 August with an average duration of 250 min, and ranging from 63 min to 370 min. Averages and standard deviations across the five systems were 234 ± 131, 262 ± 131, 498 ± 210, 655 ± 367, and 943 ± 498 ug m^{-3}.

The O_3 was released between 0900 and 1600 from 29 June to 31 August, whenever wind direction was from a 90 degree sector from the southeast to southwest. These conditions were present for 15 days totaling 65 hours of exposure. The average O_3 concentrations across the plots ranged from 129 to 838 ug m^{-3} with an average ambient concentration of 105 ug m^{-3} during exposure hours.

b. Pollutant Control and Maintenance

Tests indicated that the system could produce simulated SO_2 exposures with temporal and spatial fluctuations similar to ambient fumigations. The magnitude of the fluctuations could be controlled to some extent by the SO_2 flow rate through the system. Interpretation of the results from plume effects required careful characterization of the SO_2 concentration and duration of exposure for specific locations across the plots. However, once the exposure was quantified, it could readily be used for regression equations to evaluate plant responses. The system was flexible and could be adapted for different uses by altering the number of pipes in the array.

The system performed well with O_3 exposures as well. The main drawbacks were the amount of O_3 which would be required to be generated for any long-term study, and the inability to produce an O_3 treatment at a concentration lower than ambient.

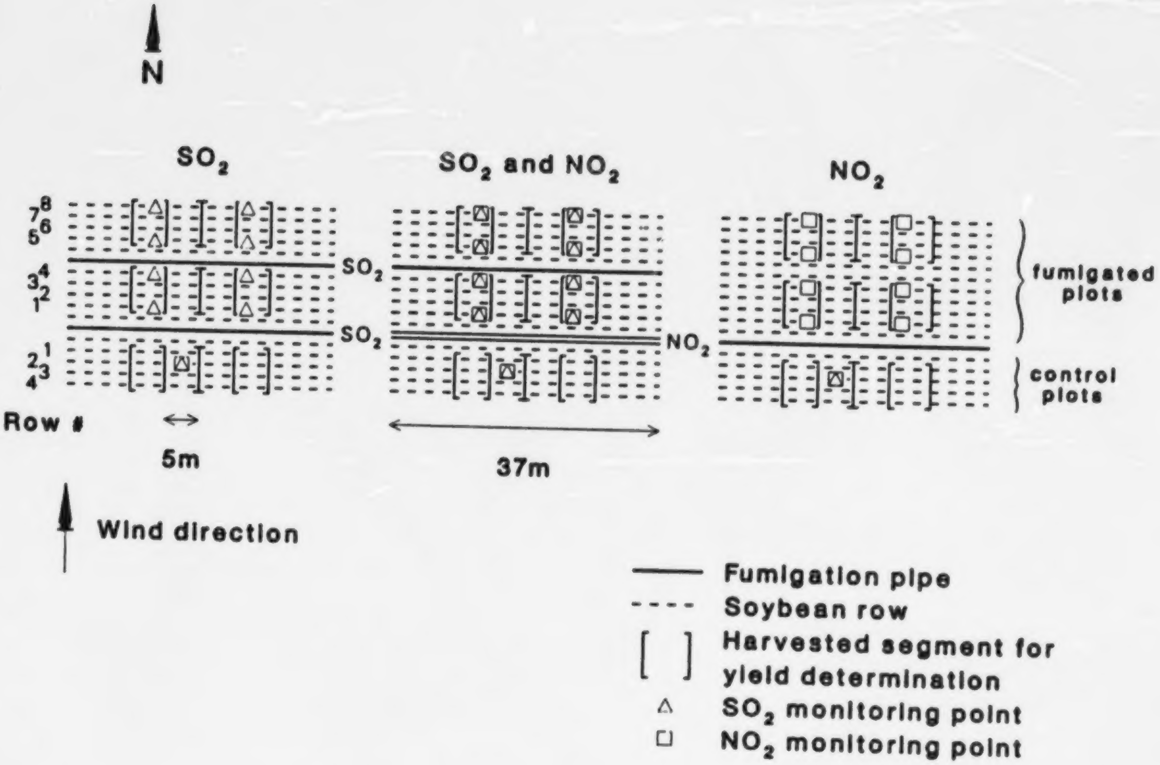


Figure A-4. Schematic diagram of plot layout for linear plume system for SO_2 and NO_2 interaction exposures (reprinted from Irving and Miller, 1983, with permission of Canadian Journal of Botany).

Publication: Moser, T. J., T. H. Nash, and W. D. Clark. 1980. Effects of long-term field sulfur dioxide fumigation on Arctic caribou forage lichens. Can. J. Bot. 58:2235-2240.

Location: University of Arizona, Tempe, Arizona; site at Anaktuvuk Pass, Alaska

Summary: A plume exposure system is described to expose Arctic lichens to SO_2 *in situ*. The system is a single length of pipe delivering SO_2 from a tank of SO_2 equipped with a regulator valve. Lichens are sampled from a grid south of the pipe. Concentrations of SO_2 over the grid are checked under a range of meteorological conditions.

1. Plots

The exposure plot is 1.0 x 5.0 m. Five 0.2 x 0.6-m sampling areas are established in the center of the plot at 0.3-0.5, 1.0-1.2, 2.0-2.2, 3.0-3.2, and 4.0-4.2 m from the SO_2 source.

2. Hardware

a. Emitters

The aluminum emitter tube is 1.0 m long with 0.0008-m diameter holes paired every 0.1 m along the bottom of the pipe. The pipe is fitted with adjustable legs and positioned 0.05 m above the lichen mat.

b. Pollutant Dispensing and Monitoring

Sulfur dioxide is supplied to the pipe from a tank of SO_2 via a regulator valve. The SO_2 exposure is continuous for 36 days. An electroconductimetric analyzer is used for SO_2 monitoring. Monitoring is not continuous, but rather conducted under a variety of weather conditions to establish the general pattern of SO_2 exposure over the plot.

c. Environmental Control and Monitoring

The environment is neither controlled nor monitored.

d. Data Aquisition

Manual.

3. Performance Evaluation

a. Pollutant Uniformity

Sulfur dioxide is monitored for over 55 h including 43.4 h of downwind analysis and 11.9 h of upwind analysis. The mean SO_2 concentration upwind of the source has ranged from 231 ug m^{-3} near the pipe to 1.8 ug m^{-3} when measured 4.1 m from the pipe. The mean downwind concentrations have ranged from 2699 ug m^{-3} near the pipe to 173 ug m^{-3} at 4.1 m from the pipe. Variation in concentration at the sampling points over time is > 100% upwind of the pipe and 50-70% downwind of the pipe.

b. Pollutant Control and Maintenance

Not described.

Publication: Northrop Services, Inc. 1983. Work Assignment 5. Air Quality Related Values. Air Pollution Fumigation Studies #1. PX-0001-2-0725. Final Project Report SP-4162-813-08. For National Park Service, Air and Water Quality Division, Under Contract CX-0001-1-0112. Bennett, J. Personal communication.

Location: National Park Service, Denver, Colorado

Summary: A portable plume system for use in native plant communities has been designed and tested under contract to the National Park Service. The system consists of a series of three emitter tubes that can be positioned horizontally or vertically depending on vegetation type. The system is controlled by a computer feedback system to emit SO_2 or O_3 depending on wind speed and direction. The theoretical basis and testing of the system in several different environments is described in detail.

1. Plots

The system could be placed horizontally to enclose a 8 x 15 m area with the plume extending downwind, or vertically to provide a plume emitted between 0 and 10 m high on one end of the plot.

a. Emitters

The emitters are three 15-m long PVC delivery pipes attached 4 m apart to a head pipe. The pollutant is released from 0.003-m diameter holes every 0.5 m along one side of the pipe.

b. Pollutant Dispensing and Monitoring

Sulfur dioxide is obtained from a tank of liquid SO_2, and delivered to the emitters via a pressure regulator, rotameter, and solenoid for computer control. Ozone is generated by UV irradiation of air, with the emission rate determined by the number of bulbs in operation. Dilution air is provided to the polluted air by a 2.8 m^3 min^{-1} capacity blower. The pollutants from a number of sample points are analyzed via a series of solenoids.

c. Environmental Control and Monitoring

Wind speed and direction, temperature, relative humidity, and solar irradiation are monitored continuously.

d. Data Acquisition

Pollutant concentration data are processed and controlled by an interface and microcomputer. The microcomputer system also stores environmental data.

3. Performance Evaluation

a. Pollutant Uniformity

Pollutant concentrations over the exposure plot vary five-fold over 10 days of fumigation when the system was used in the horizontal mode. No information is available on dispersion with the vertical mode, or for exposures over an extended period.

b. Pollutant Control and Maintenance

Further development and testing are suggested for this plume system. A major drawback of the system is the inability to model the pollutant plume in natural ecosystems, especially a forest canopy. This results in a lack of definition of pollutant doses to target plant material over the entire exposure area.

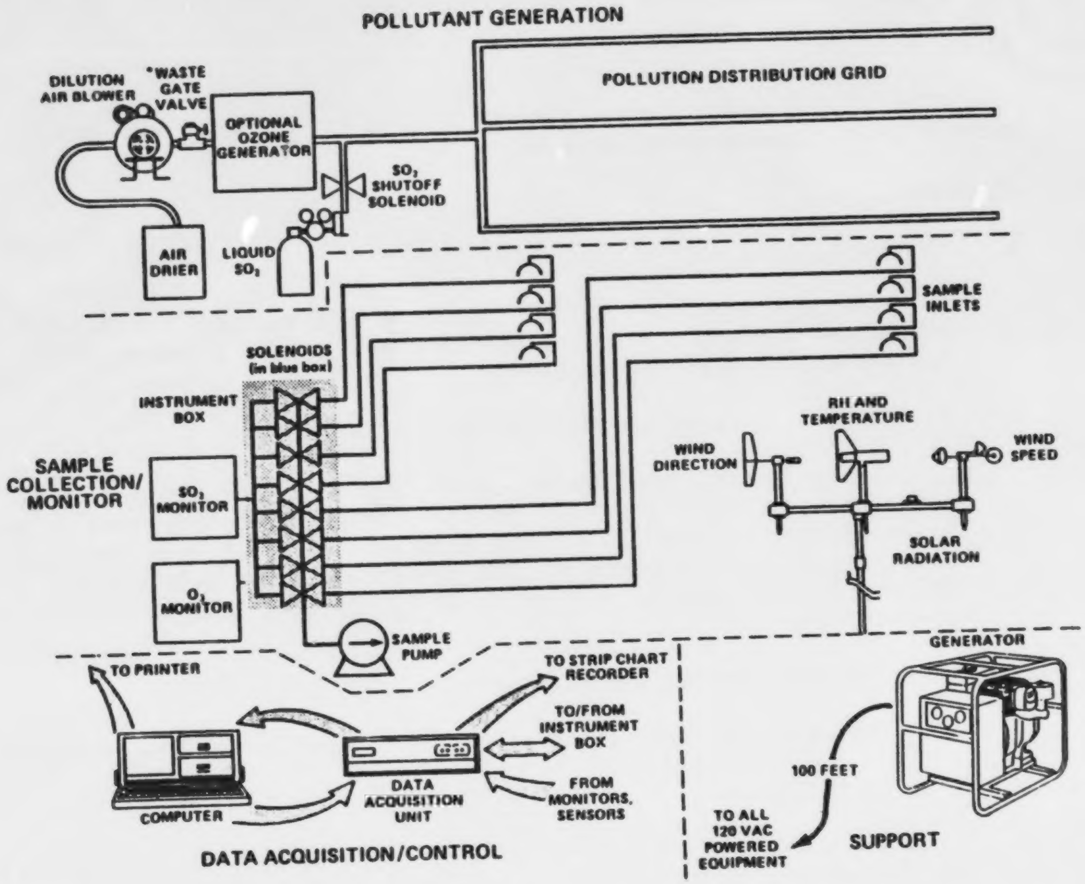


Figure A-5. Schematic diagram of plume system developed for the National Park Service (Northrop, 1983).

Publication: Roberts, T. M. 1985. Open Air Forest Fumigation Experiment. Personal communication.

Location: Central Electricity Research Laboratories, Leatherhead, England. Experimental plots at Liphook.

Summary: A large-scale plume system is being constructed to expose trees to SO_2 and/or O_3 in the field for up to five years.

1. Plots

Five 50-m diameter exposure plots will be established, each with a central 25-m diameter sampling area.

2. Hardware

a. Emitters

The pollutant emitters will be in a 50-m diameter circle with heights of 1.0 and 2.5 m. The emitters will be PVC pipes in four individually controlled sections.

b. Pollutant Dispensing and Monitoring

Sulfur dioxide will be delivered from tanks through mass flow controllers, with flow to each emitter controlled by solenoid valves. Ozone will be produced by a large generator with output proportionally controlled by a computer, and delivered to the emitters via solenoids. Air samples will be moved by sampling pumps and valves to analyzers.

c. Environmental Control and Monitoring

Environmental conditions will be monitored during the exposures.

d. Data Aquisition

All pollutant dispensing, control, monitoring, and data storage, as well as environmental monitoring, will be by microcomputer.

3. Performance Evaluation

a. Pollutant Uniformity

Not described.

b. Pollutant Control and Maintenance

Not described.

Publication: Runeckles, V. C., K. T. Palmer, and H. Trabelsi. 1981. Effects of field exposures to SO_2 on Douglas fir, *Agropyron spicatum*, and *Lolium perenne*. Sil. Fen. 15:505-515.

Location: University of British Columbia, Vancouver, British Columbia

Summary: Research at the University of British Columbia has focused on development of a field exposure system relevant to the crops and environmental conditions of the province. Open-top field chambers have not proven useful especially due to the enhanced greenhouse effect during cool months. A plume was developed first for use with SO_2, and has been subsequently adapted for O_3. The system uses a grid of emitter points on perpendicular and parallel tubes on a horizontal plane, similar to the Lee *et al*. (1975) system.

1. Plots

Exposure plots are rectangular, 10 x 12 m, with four plots located 25 m apart in a field.

2. Hardware

a. Emitters

The plume system consists of an array of PVC tubes positioned horizontally, parallel and perpendicular to each other as described by Lee *et al*. (1975). The tubes are 1.0 m above the soil. There are two outer 12-m long tubes and an inner 10-m long tube. Other 3.0-m long tubes cross the longer tubes at 3.0-m intervals. The pollutant is emitted at 1.0-m intervals from 0.0008 m diameter holes. The system originally was constructed for SO_2 exposures, but is currently being used to expose plants to O_3.

b. Pollutant Dispensing and Monitoring

Sulfur dioxide is dispensed from a tank of pure SO_2 diluted with compressed air via a manifold to low, medium, and high concentration plots. Samples of SO_2 are drawn from each plot via a time-sharing device and analyzed with a pulsed fluorescence analyzer. For the current O_3 studies the pollutant concentration is controlled by a computer feedback system.

c. Environmental Control and Monitoring

Measurement of meteorlogical variables is discussed in the text, but no indication of conditions is given.

d. Data Acqusition

Pollutant concentrations and environmental conditions are recorded by a datalogger and microcomputer system.

3. Performance Evaluation

a. Pollutant Uniformity

Sulfur dioxide concentrations vary by 5-15% across plots. No indication of vertical or temporal variation is given; however, a frequency distribution is presented of the sulfur dioxide concentrations through the growing season.

b. Pollutant Control and Maintenance

There is considerable variability in SO_2 concentrations throughout the growing season. However, distributions are log-normal for all three plots providing variability in SO_2 concentrations that could be representative of fumigation episodes.

See original publication for schematic of exposure system (reprint permission was not obtained).

Publication: Thompson, C. R., D. M. Olszyk, G. Kats, A. Bytnerowicz, P. J. Dawson, and J. W. Wolf. 1984. Effects of O_3 or SO_2 on annual plants of the Mojave Desert. J. Air Pollut. Contr. Assoc. 34:1017-1022.

Location: University of California, Riverside; field site at at Daggett, California

Summary: A computer-controlled plume system was designed, constructed, and tested for use with annual and perennial vegetation in the Mojave Desert. The system has a linear configuration, releasing the plume over plots only when the wind is from the west. The system is computer controlled depending on wind speed, wind direction, and pollutant concentration at a dedicated point. The system has been used for SO_2 exposures and is being adapted for O_3 exposures.

1. Plots

The exposure plots are rectangular, 3.1 x 7.6 m, with a total area of 23.6 m^2. Four to seven plots are positioned north to south at the research site.

2. Hardware

a. Emitters

The system consists of a single bank of two levels of emission tubes at one end of each exposure plot. The system is greatly simplified from that of Lee and Lewis (1976) as it is designed for use in the Mojave Desert where the prevailing wind direction is usually from the west. Each system is fabricated from two 3.1-m long x 0.0013-m diameter PVC tubes placed parallel 0.25 m apart with the lower tube 0.45 m above the ground. The tubes have pin-hole perforations 0.15 m apart on the side facing the exposure plots. The emission tubes are placed 7.1 m from the west edge of the plots.

b. Pollutant Dispensing and Monitoring

The SO_2 is released from the plume system only with the pressure from the compressed SO_2 tank. The system relies solely on ambient wind movement for pollutant dispersion. The plume has been operated with a computer-controlled feedback system to provide exposures only when wind is blowing within a specific range of degrees from the west. For one desert plant study three Zonal Air Pollution plots were used with target average concentrations of 1310, 2620, and 5240 ug m^{-3} SO_2. The SO_2 concentrations are controlled via a dedicated sample point in the low concentration plot. The air sample from this point is analyzed via a dedicated Meloy Model SA85 sulfur analyzer. The signal from the SO_2 analyzer is processed by an Issac® S91A interface and Apple IIe® microcomputer system where it is compared to a set point. Based on relationship to the set point (1310 ug m^{-3} SO^2), wind direction (west), and wind speed (> 5 mph); a mass flow controller is activated to release more or less SO_2 from the system.

Sulfur dioxide is dispensed from a cylinder of 100% gas enclosed in an insulated, thermostated galvanized steel can via a pressure reducer prior to the mass flow controller. From the controller SO_2 enters a manifold. Sulfur dioxide is monitored continuously with an array of sampling points across the plots. The samples are processed by a scanning valve and Meloy SA85 sulfur analyzer.

c. Environmental Control and Monitoring

In one study, soil moisture level is controlled by differential watering. Environmental conditions are continuously monitored for all studies, including air temperature, dewpoint, wind speed, and wind direction.

d. Data Acquisition

Pollutant dispensing, monitoring, data storage, and processing are controlled by an interfaced-microcomputer system. Environmental conditions are monitored and the data stored and processed by the computer system.

3. Performance Evaluation

a. Pollutant Uniformity

The plume has worked well to produce three levels of SO_2 exposure similar to events that could occur from a point source in the desert. Initially, the exposures lacked precision and the system could not attain the desired concentrations and resulted in exposures to 1048, 2096, and 2620 ug m^{-3} SO_2 in the low, medium, and high plots. The exposures have occurred over 37 hours spread over 6 exposure days. The variability among hourly-average concentrations has ranged up to 70% per treatment, and from 40-90% horizontally across entire plots.

b. Pollutant Control and Maintenance

Subsequent testing has resulted in increased precision by increasing the distance between the plume and end of the plots to reduce variability across the plots, decreasing the range of degrees for which SO_2 would be released, and placing Dustamer® "snow fence" material between plots to a height of 1.0 m to "channel" the pollutants down the plots. Also, enhanced pollutant sampling across the plots allows for more precise identification of the pollutant concentrations which a particular plant in the plot receives. Thus, variability in pollutant concentration can be used to provide a wider range of exposures for statistical analysis of the plant responses by regression analysis of individual plant data.

Currently the plume system is being modified to provide exposures to O_3 in the Mojave Desert. An Orec Model O_3 generator with tank oxygen will be used as the O_3 source. The same plume configuration and computer feedback control system is being used as described for SO_2. A set point of 198 ug m^{-3} will be used to test the system. The system is being tested to evaluate the amount of O_3 required to simulate ambient O_3 episodes, the dispersion of O_3 over the plots, ability to control the O_3 generator via an electronic signal, deterioration of the PVC pipe with O_3 exposures and other considerations.

Use of this simplified plume system for O_3 exposure appears to be appropriate for the Mojave Desert where O_3 episodes are periodic; following transport of pollutants from the Los Angeles basin to the west. This plume configuration would not be appropriate for areas where O_3 episodes are a regional phenomenon occurring with winds from different directions. Furthermore, this system has not been tested for daily exposures over a growing season, as would occur in many regions of the U.S.

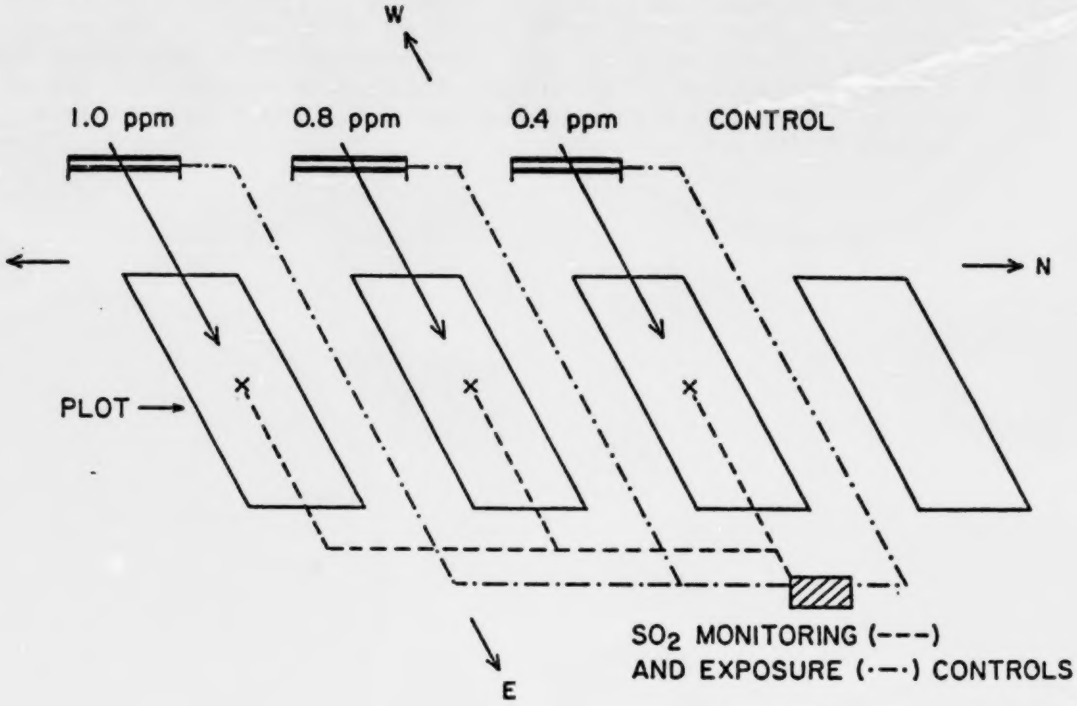


Figure A-6. Schematic diagram of linear plume system for desert plants (reprinted from Thompson et al., 1984, with permission of Air Pollution Control Association).

APPENDIX B

Descriptions of Facilities and Performance Evaluations -- Air Exclusion Systems for Gaseous Dry Deposition Research

Publication: Jones, H. C., N. L. Lacasse, W. S. Liggett, and F. Weatherford. 1977. Experimental air exclusion system for field studies of SO_2 effects on crop productivity. U.S. Environmental Protection Agency, Washington, D.C. EPA-600/7-77-122.

Location: Tennessee Valley Authority (TVA), Muscle Shoals, Alabama

Summary: A non-chambered air exclusion system was designed and tested to determine the effects of ambient SO_2 on crops. The system uses a high pressure blower and PVC ducts between rows to blow filtered air over a soybean canopy only during SO_2 fumigation episodes. The system is successful in excluding up to 85% of the ambient SO_2.

1. Hardware

a. Ducts

The system consists of a blower box and four PVC ducts lying between and alongside four rows of soybeans. The ducts are 7.6 m long and 0.33 m in diameter with 0.0025-m diameter holes spaced 0.31 m apart. For one test the ducts had one row of 24 holes directed perpendicularly up from the ground. For other tests the ducts had two rows of 24 holes each at 45° angles from horizontal for two middle ducts and the center facing sides of the outer ducts, holes at 90° angles for the outer sides of the outer ducts. The ducts are inflated by a 1.5 hp blower delivering 122 m^3 min^{-1} flow. Filtered air systems are equipped with charcoal filters and all systems are equipped with dust filters.

b. Pollutant Dispensing and Monitoring

Pollutants are not added to this system. Sulfur dioxide is monitored with a Phillips SO_2 analyzer, ozone with a chemiluminescent analyzer.

c. Environmental Control and Monitoring

The environment is not controlled by the system; however, soil moisture, air temperature, solar radiation, and relative humidity are measured during the exposures.

d. Data Acquisition

Pollutant data are saved with a datalogger.

2. Performance Evaluation

a. Pollutant Uniformity

The system excludes up to 83% of the ambient SO_2 at the top of the plant canopy. Sulfur dioxide is to some extent trapped beneath the plant canopy, and concentrations increased by 10% nearer to the soil.

b. Environment Uniformity

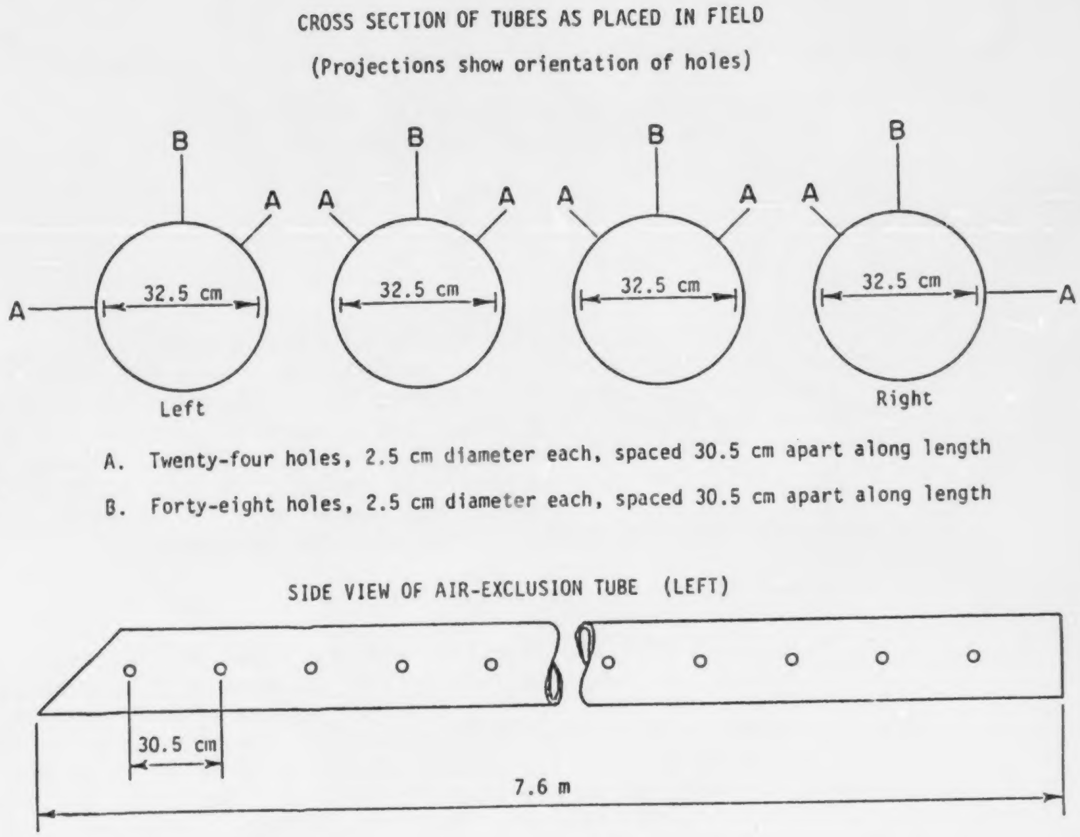
Not described.

c. Pollutant Control and Maintenance

The feedback relay system works well for turning on the air exclusion system only during SO_2 fumigation episodes. Further tests of the system are suggested, especially to characterize the vertical distribution of pollutants in the canopy.

d. Environmental Control and Maintenance

Not described.



CROSS SECTION OF TUBES AS PLACED IN FIELD

(Projections show orientation of holes)

A. Twenty-four holes, 2.5 cm diameter each, spaced 30.5 cm apart along length

B. Forty-eight holes, 2.5 cm diameter each, spaced 30.5 cm apart along length

SIDE VIEW OF AIR-EXCLUSION TUBE (LEFT)

Figure B-1. Schematic diagram of emitter tubes for air exclusion systems (Jones *et al.*, 1977).

Publication: Laurence, J. A., D. C. MacLean, R. H. Mandl, R. E. Schneider, and K. W. Hansen. 1982. Field tests of a linar gradient system for exposure of row crops to SO_2 and HF. Water, Air, Soil Pollut. 17:399-407.

Additional Publication: Reich, P. B., R. G. Amundson, and J. P. Lassoie. 1982. Reduction in soybean yield after exposure to ozone and sulfur dioxide using a linear gradient exposure technique. Water, Air, Soil Pollut. 17:29-36.

Location: Boyce Thompson Institute, Ithaca, New York

Summary: An exposure system is described for adding O_3, SO_2, or HF to a plant canopy. The system has a blower and mixing box, and three ducts alongside two rows of test plants.

1. Hardware

   a. Ducts

      The blower box contains two 14 m^3 min^{-1} blowers and a box where ambient air mixes with injected pollutants. Three PVC ducts are attached to exit ports on the mixing box. The ducts are 0.15 m in diameter and 13 to 15.4 m long, depending on pollutant. Air exits the ducts from a combination of 0.009- and 0.00625-m diameter holes in two rows. The hole surface area ranges from 0 to 0.232 m^2 m^{-1} along the length of the duct. The center duct has holes on both sides, the outer duct only on the side facing plants.

   b. Pollutant Dispensing and Monitoring

      The pollutants are injected into the meter of the mixing box. Sulfur dixoide is supplied from a tank, gaseous HF from a heated solution of aqueous HF, and O_3 from oxygen gas passing over an ultraviolet light source. Sulfur dioxide is monitored with flame photometric or pulsed-fluorescent analyzers, HF flux to static samples is measured by wet chemistry methods, and O_3 is measured with a chemiluminescent analyzer. Multiple pollutant sampling locations are distributed over the exposure plot. Air is sampled from each point with a sequential sampler.

   c. Environmental Control and Monitoring

      Not described.

   d. Data Acquisition

      Not described.

2. Performance Evaluation

a. Pollutant Uniformity

Pollutant concentrations increase linearly along the length of the ducts. Sulfur dioxide concentrations increase from 0 to 1572 ug m^{-3} along the duct. This increase is reflected in a doubling of leaf total sulfur content. There is a similar increase in static HF concentrations and fluoride content of leaf tissue. At a monitoring point 11 m from the blower box, SO_2 concentrations decrease by 50 to 67% with an increase in height from 0.2 to 0.9 m above the outside ducts, but remain the same with an increase in height above the middle duct. Sulfur dioxide and O_3 concentrations in plots vary by 100 to 400% over low, medium and high pollutant zones of a linear gradient system based on frequency distributions, with the greatest variation in the high concentration zones.

b. Environment Uniformity

Not described.

c. Pollutant Control and Maintenance

The duct system provides for a controlled gradient of pollutant concentrations within a plant canopy. The gradient is reflected in flux of pollutants to leaves. However, the pollutant was added beneath the plant canopy and not at the top as occurs in ambient air. A comprehensive network of air sampling is required to define the pollutant exposure to particular plants.

d. Environment Control and Maintenance

Not described.

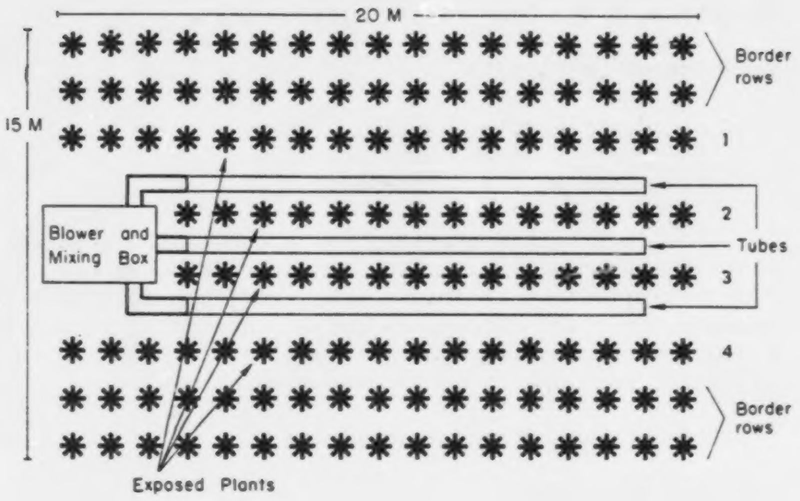


Figure B-2. Schematic diagram of air exclusion system for exposure of plants to linear gradients of pollutants (SO_2, HF, O_3) (reprinted Laurence et al., 1982, with permission of D. Reidel Publishing Co., Dordrecht, Holland).

Publication: Shinn, J. H., B. R. Clegg, and M. L. Stuart. 1977. A linear-gradient chamber for exposing field plants to controlled levels of air pollutants. UCRL Reprint No. 80411. Lawrence Livermore Laboratory, University of California, Livermore.

Additional Publications: Bennett, J. P., K. Barnes, and J. H. Shinn. 1980. Interactive effects of H_2S and O_3 on the yield of snap beans (*Phaseolus vulgaris* L.). Environ. Exp. Bot. 20:107-114.

Shinn, J. H. 1979. Problems in assessment of air pollution effects on vegetation. In: Advances in Environmental Science and Engineering, J. R. Pfaffling and E. N. Ziegler (eds.). Gordon and Breach Science Publishers, Inc. New York. pp. 88-105.

Shinn, J. H., B. R. Clegg, M. L. Stuart, and S. E. Thompson. 1976. Exposures of field-grown lettuce to geothermal air pollution -- photosynthetic and stomatal responses. J. Environ. Sci. Health (Part A). 11:603-612.

Location: University of California, Livermore, California

Summary: An air exclusion system was designed and tested for exposure of plants to a linear gradient of O_3 and/or H_2S in the field. The system has three rows of ducts, and a high pressure blower to inflate the ducts and blow filtered or unfiltered air plus added pollutants over the plant canopy. The system is surrounded by a fiberglass wall to inhibit incursion of ambient air into the exposure plot.

1. Hardware

a. Ducts

There are three ducts lying between and alongside two rows of plants. The ducts are 7.5 m long and 0.15 m wide, with 1.0 m between ducts to provide a total plant growing area of 15.0 m per system. The ducts have one row of holes oriented perpendicular to the ground and toward the crop rows. The hole sizes increase moving away from the blower box, from 0.00254 m to 0.00559 m in diameter. The flow rate in the center of the ducts decreases from the blower box to the end of the duct, but the air speed exiting the holes remains 10 m s^{-1}. Air is supplied from a blower assembly delivering 28.3 m^3 min^{-1} to the system. The blower is equipped with charcoal filters.

b. Pollutant Dispensing and Monitoring

Sulfur dioxide or H_2S are delivered to the system from tanks via regulators, a stainless steel capilary tube, and an injection tube downstream from the charcoal filter. Ozone is generated by ultraviolet lamps controlled by a variable transformer. Concentrations of H_2S were measured with a flame photometric analyzer, SO_2 with a pulsed-UV fluorescent analyzer, and ozone with a UV absorption analyzer. Monitoring from various sampling points is via a time-sharing system. Pollutant dispension is controlled with time clocks.

c. Environmental Control and Monitoring

The environment is not controlled in this system; however, ambient irradiance, air temperature, wind speed and direction are measured during exposures.

d. Data Acquisition

Not described.

2. Performance Evaluation

a. Pollutant Uniformity

The air exclusion system produces a gradient of SO_2, H_2S, or O_3 concentrations along the ducts. Horizontal variability in concentrations is from 300 to 2300% along the duct. Vertical variability is approximately 250 times from emission holes to the soil. Average pollutant concentrations in the system as a whole vary by 20% over time.

b. Environment Uniformity

There are no differences in irradiance or air temperature in the air exclusion system compared to outside.

c. Pollutant Control and Maintenance

The air exclusion system maintains a gradient of pollutant concentrations over the exposure plot. The concentrations are more variable than in a system purposely designed for uniform plant exposures throughout the plot; however, the gradient system provides pollutant exposures for regression analysis of pollutant responses.

d. Environmental Control and Maintenance

Not described.

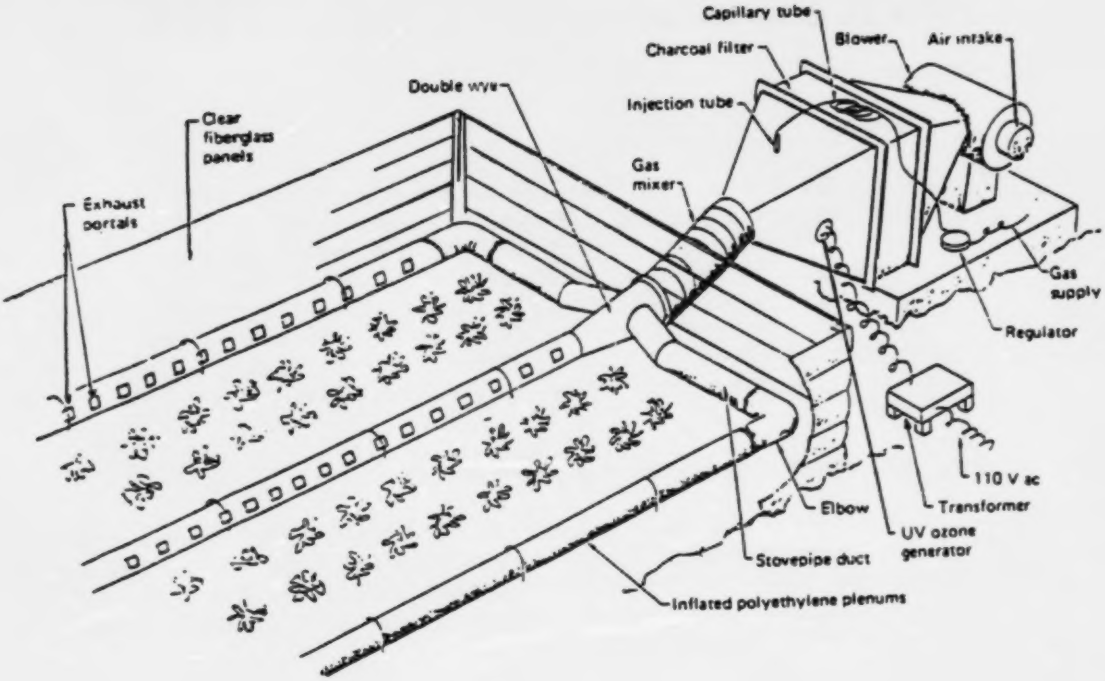


Figure B-3. Schematic diagram of air exclusion system for exposure of plants to H_2S and O_3 (reprinted from Shinn et al., 1977, with permission of University of California, Lawrence Livermore National Laboratory).

Publication: Spierings, F. 1967. Method for determining the susceptibility of trees to air pollution by artificial fumigation. Atmos. Environ. 1:205-210.

Additional Publication: Mooi, J. 1972. Investigation on the sensitivity of trees and shrubs to air pollution. (In Dutch). Inst. Phytopath. Res. Wag. Ann. Rep. 1971. pp. 169-173, 195.

Location: Institute of Phytopathological Research, Wageningen, Netherlands

Summary: A unique apparatus is described to expose portions of trees and shrubs to air pollution in the field. The system has a blower which directs polluted air towards a target branch in a "gun-like" fashion. The apparatus is a variant of an air-exclusion system with transparent plastic plates directing the air flow while blocking ambient air incursion.

1. Hardware

a. Blower

The blower box consists of a U-shaped tube with the air inlet at one end and a flaring air outlet at the other end. The tube is 0.25 m internal diameter, flaring to 0.38 m diameter at the outlet. Air flow through the tube is 30 m^3 min^{-1}. The blower is positioned so that the direction of the air flow to the branch parallels the wind direction. Clear square plastic baffles extending from the flared outlet of the blower direct the air stream toward a particular branch and prevent a change in ambient wind direction from altering the air flow.

b. Pollutant Dispensing and Monitoring

Sulfur dioxide is injected into the blower through four holes equidistant around the perimeter of a PVC tube encircling the inside of the tube near the inlet and just before the fan. The sulfur dioxide concentration of the air stream at the target branch is determined by wet chemistry.

c. Environmental Control and Monitoring

Air temperature and relative humidity are recorded during exposures.

d. Data Acquisition

Not described.

2. Performance Evaluation

a. Pollutant Uniformity

The average pollutant concentrations for target branches vary by approximately 5 to 9% over a wide range of exposures with 1310 to 3747 ug m^{-3} SO_2.

b. Environment Uniformity

Not described.

c. Pollutant Control and Maintenance

Not described.

d. Environmental Control and Maintenance

Not described.

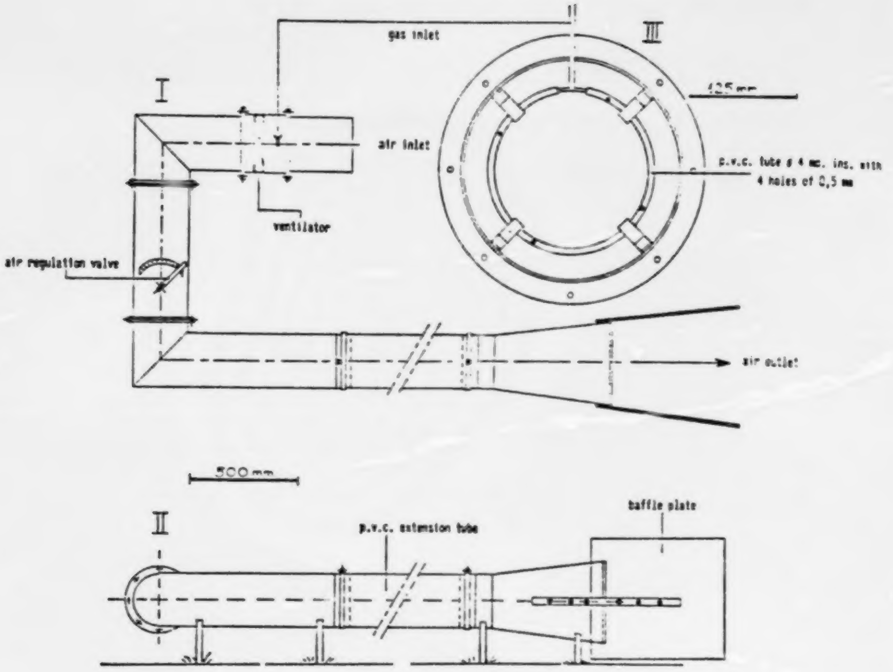


Figure B-4. Schematic diagram of "gun" air-exclusion system showing top view (top) and side view (bottom) (reprinted from Spierings, 1967, with permission from Pergamon Press).

Publication: Thompson, C. R., and D. M. Olszyk. 1985. A Field Air-Exclusion System for Measuring the Effects of Air Pollutants on Crops. EPRI EA-4203. Final Report for Project 1908-3. Electric Power Research Institute. Palo Alto, California.

Location: University of California, Riverside, California

Summary: The system has been designed to exclude ambient pollutants and add pollutants along a linear gradient. The system is based on the Tennessee Valley Authority (TVA) system (Jones et al., 1977), but has been substantially modified to increase the efficiency of air exclusion, provide for exposure of greater numbers of plants, and be more portable and flexible for different uses. This air-exclusion system has been compared to open- and closed-top chambers for the degree of environmental modification and plant response to air pollutant with exposures during all seasons of the year.

1. Hardware

a. Ducts

The basic system consists of four major components: a module containing the filters, a blower for air supply, a manifold for air distribution, and perforated ducts to deliver the air to the target area. The filter module is fabricated of galvanized sheet-metal to form an approximate 0.6-m cube. The module contains three 0.61 x 0.61 x 0.2 m corrugated activated carbon filters each with 20.4 kg of 6-mesh coconut charcoal. Glass furnace filters and strainer mats protect the charcoal-filters from dust. A 2-hp, three-phase blower (0.8-m diameter wheel with backward curved blades) is installed in an adjacent approximate 0.6-m cube area. A sheet metal duct leads from the blower to a 1.82 x 0.61 x 0.61 m mixing manifold. The manifold has four short galvanized metal exhaust ports for attaching plastic duct. Butterfly valves are installed in each exhaust port to regulate the flow into each duct. The free air delivery into the entire system is 57 m^3 min^{-1}.

There are four ducts for all pollutant exposures, with three rows of holes pointed at 45° down, 90° and 45° from horizontal. There are rows of holes on either side of the two center ducts and on the plant canopy side of the outer ducts. The ducts are 0.32 m in diameter, and made of PVC with a metal bar placed inside to stabilize them against wind. The ducts are 0.41 m apart. The length of the ducts, hole spacing, hole diameter, and division of the duct into sections for a gradient differs for each experiment. A general configuration for ambient O_3 exclusion studies has 9.1-m long ducts, and 0.022-m diameter holes 0.15 m apart. The system provides a gradient of ambient O_3 exclusion by dividing the duct into three sections with sequentially larger holes of 0.011, 0.019, and 0.032 m diameters. A sulfur dioxide linear gradient is provided by dividing the duct into four sections with metal baffles, and injecting SO_2 into the duct at different distances from the blower to achieve 0, 79, 183, and 393 ug m^{-3} concentrations.

b. Pollutant Dispensing and Monitoring

No pollutant dispensing is required for the ambient O_3 exclusion test. Ozone is measured at a number of sample points with a scanning valve and UV absorption analyzer. For SO_2 gradient studies, SO_2 is supplied from a heated tank via a mass flow controller and needle valve to a mixing Venturi filled with dried, compressed air. The SO_2 is injected into metal baffles at the beginnings of the low, medium, and high SO_2 concentration portions of the duct. Each injection tube is equipped with hypodermic tubing and a length of 0.0032-m diameter PVC tubing. The gas dispensing rate into a particular baffle is regulated by varying the length of the hypodermic tubing at a constant SO_2 gas pressure. Sulfur dioxide at a number of sampling points is measured with a scanning-valve and interface-microcomputer system.

c. Environmental Control and Monitoring

The environment is not controlled in this system. However, controlling the air flow from the duct holes can alter dew formation and fog intercept by leaves. Wind speed, air temperature, soil temperature, leaf temperature, irradiance, and relative humidity are measured routinely during exposures.

d. Data Acquisition

Ozone and SO_2 are monitored and SO_2 exposures are controlled by an interface-microcomputer system. All pollutant concentrations, and air and leaf temperature data are processed and stored by the computer system.

2. Performance Evaluation

a. Pollutant Uniformity

The air-exclusion systems effectively exclude up to 80% of the ambient pollution from the plant canopy based on ambient O_3 and CO addition tests. Within the plant canopy (0.05 to 0.4 m above the ground) there is a 10% difference in pollutant concentrations. Over entire growing season there is 10% variability in added pollutant concentrations to plots based on hourly-average values for SO_2.

b. Environment Uniformity

The air speed over the plant canopy is approximately 1 m s^{-1}. Air temperature is similar in the air-exclusion systems and outside plots (ambient) during the summer and fall, and up to 1.5°C warmer in the air-exclusion systems during the winter compared to outside plots. Soil and leaf temperatures are similar in the air-exclusion systems and the outside plots during the summer, and 1 to 2°C higher in the air-exclusion systems in the winter. Irradiance generally is > 94% of ambient during most periods of time. Relative humidity is the same in the air-exclusion systems and outside plots.

c. Pollutant Control and Maintenance

Pollutant concentrations are similar to those that could be achieved in open- or closed-top chambers, in terms of both ambient and added pollutants. There generally is greater variability in pollutant concentrations in the air-exclusion system than chambers due to more ambient incursion with high winds. However, the variability is more representative of ambient conditions and can be monitored and documented with the microcomputer data-aquisition system.

d. Environmental Control and Maintenance

Uniform environmental conditions can be maintained as easily with the duct systems as with open-top field chambers. Wind speeds over the crop canopy are much more variable with air-exclusion systems than chambers due to ambient wind incursion; however, this variability may be more representative of ambient conditions than a constantly uniform air flow rate over a plant canopy.

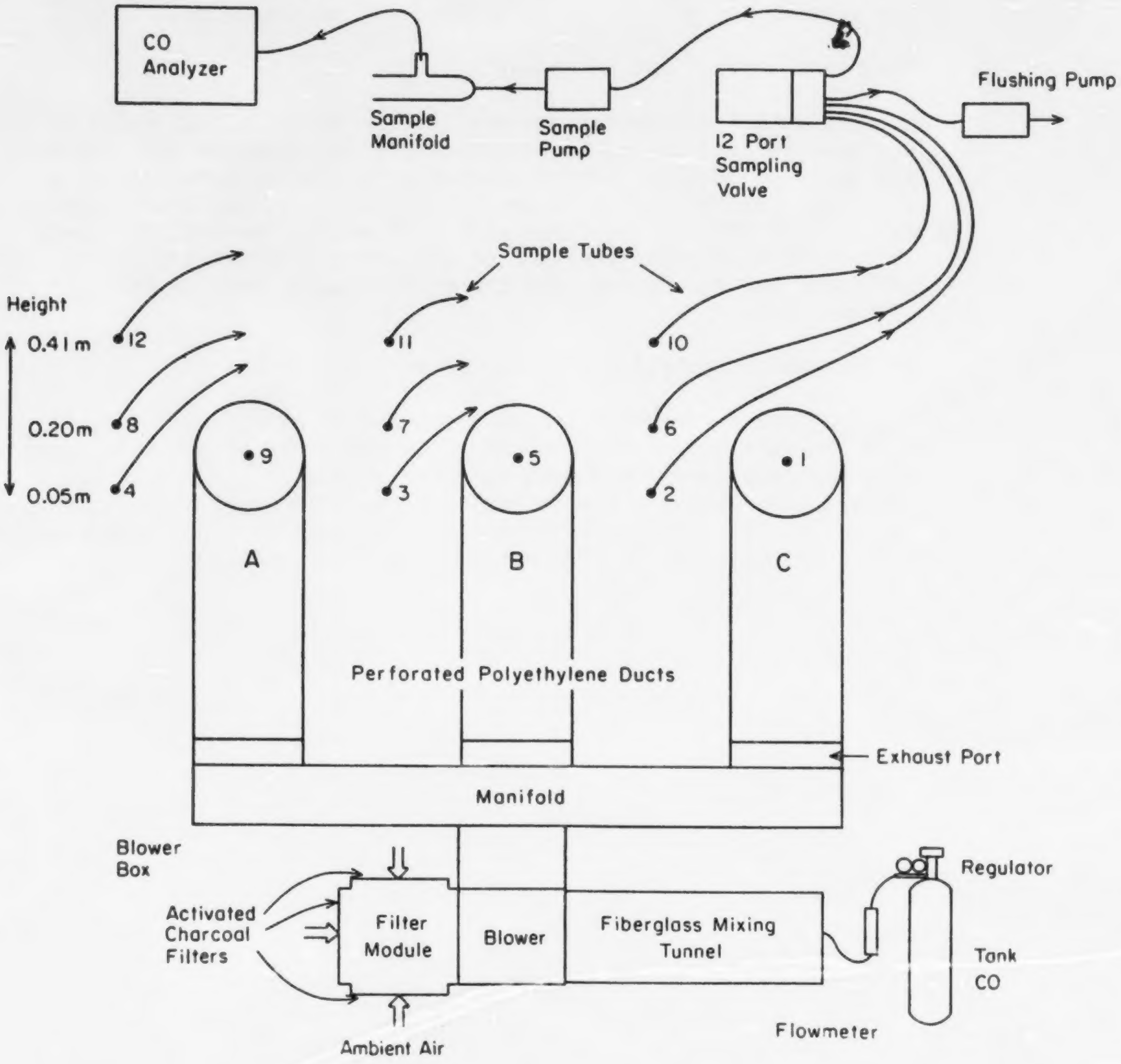


Figure B-5. Schematic diagram of air exclusion system for oxidant exclusion and SO_2 addition (reprinted from Thompson and Olszyk, 1985, with permission of authors and Electric Power Research Institute).

APPENDIX C

Descriptions of Facilities and Performance Evaluations -- Outdoor Chambers for Gaseous Dry Deposition Research

Publication: Brewer, R. F. 1978. The Effects of Present and Potential Air Pollution on Important San Joaquin Valley Crops: Sugar Beets. Final Report to California Air Resources Board. Project A6-161-30. Sacramento.

Location: University of California Experiment Station, Parlier, California

Summary: A square base, circular top, open-top field chamber has been designed for use with sugar beets and other crops.

1. Hardware

   a. Chambers

      The chambers are 3.8 m^2 at the base and 2.4 m high. The sides taper upward to a 3.1-m circular open top. The chambers are covered with PVC film. Blowers equipped with charcoal filters deliver 34 m^3 min^{-1} to each chamber. Air is delivered to the chamber between rows of plants via 0.15- and 0.20-m diameter perforated PVC pipe.

   b. Pollutant Dispensing and Monitoring

      Combinations of filtered and nonfiltered air are used as treatments; pollutants are not added to the chambers. Ozone is monitored in different chambers via solenoid valves and an ultraviolet analyzer.

   c. Environmental Control and Monitoring

      The environment is not controlled in these chambers. Air temperature, relative humidity, irradiance, and air speed are measured during exposures.

   d. Data Aquisition

      Manually by recorders.

2. Performance Evaluation

   a. Pollutant Uniformity

      Not described.

   b. Environment Uniformity

      Air temperatures are 0.5 to 1.0°C higher in chambers than outside. Relative humidities are 3 to 4% higher than outside at night and 4 to 5% lower than outside from midday to 6 p.m. Irradiance is within 85 to 93% of outside. Air speed over the plant canopy is approximately 0.3 m s^{-1} in chambers.

c. Pollutant Control and Maintenance

The chambers effectively exclude over 75% of the ambient ozone. The square design apparently provides for exposures similar to cylindrical chambers, but with more plant growing area.

d. Environmental Control and Maintenance

The open-top chambers provide environmental conditions similar to outside and relatively uniform over time.

e. Chamber Equilibration

There are 2 air exchanges per minute.

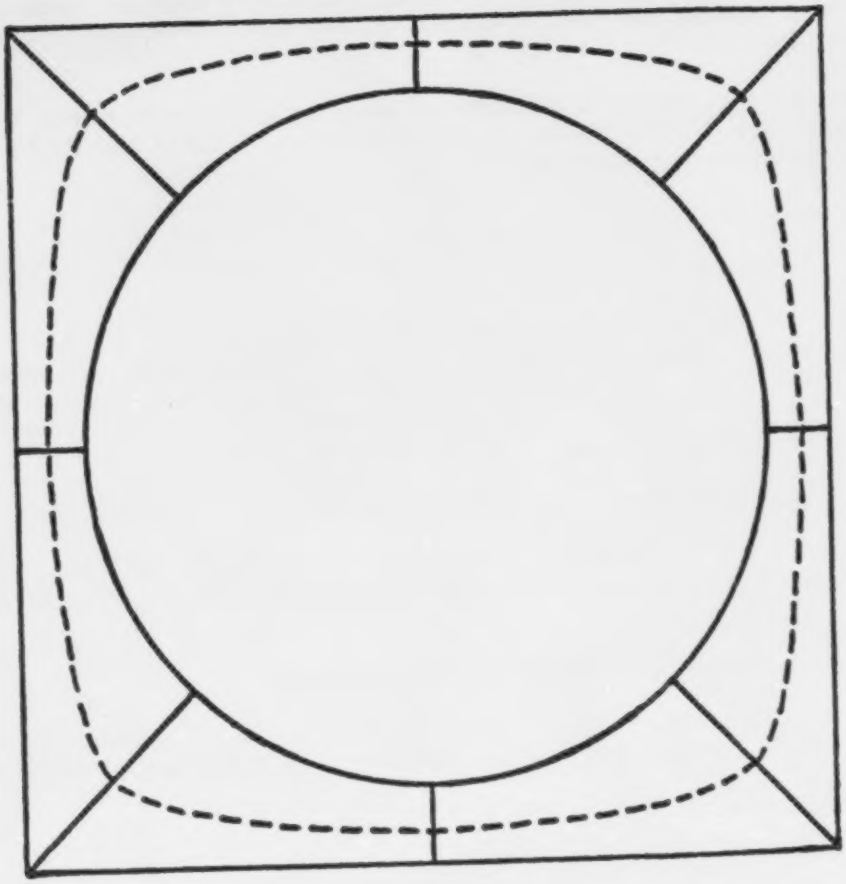


Figure C-1. Schematic diagram of open-top field chamber for sugar beets (Brewer, 1978).

Publication: Brewer, R. F. 1983. Effect of Ambient Air Pollutants on Thompson Seedless Grapes. Final Report to California Air Resources Board. Project A1-132-133. Sacramento.

Location: University of California Experiment Station, Parlier, California. A similar 7.32 m long, 2.74 m wide, and 4.27 m high rectangular chamber with a frustum has been developed at the Boyce Thompson Institute, Ithaca, New York.

Summary: A large rectangular open-top chamber has been designed for use with grapevines. The chamber has been used for filtered and nonfiltered exposures over a four-year period.

1. Hardware

   a. Chambers

      The open-top chambers are rectangular, 3.1 x 7.3 m, and 3.1 m high. They have aluminum frames, a redwood base, and are covered by PVC film. Air enters the chamber from a plenum (double-walled PVC) around the lower 1.2 m of the chamber wall. Either charcoal-filtered or nonfiltered air is blown into the chambers at 127 m^3 min^{-1}.

   b. Pollutant Dispensing and Monitoring

      No pollutants are added to the chambers. Ozone is monitored with an ultraviolet absorption analyzer using clock-controlled solenoids.

   c. Environmental Control and Monitoring

      The environment is not controlled in the chambers. Air temperature, irradiance, and air speed are measured during exposures.

   d. Data Acquisition

      Manually with recorders.

2. Performance Evaluation

   a. Pollutant Uniformity

      Not described.

   b. Environment Uniformity

      Air temperatures are 0.5 to 1.0°C higher in chambers versus outside. Irradiance is slightly lower in chambers than outside. Air speed is greater in chambers than outside during the night and early morning, but lower in chambers during the day.

c. Pollutant Control and Maintenance

No information on O_3 concentrations is given.

d. Environmental Control and Maintenance

The environment in the chambers is similar to outside. The only apparent chamber-related plant growth response is 7 to 10 days earlier bud break and bloom.

e. Chamber Equilibration

There are 2 air exchanges per minute.

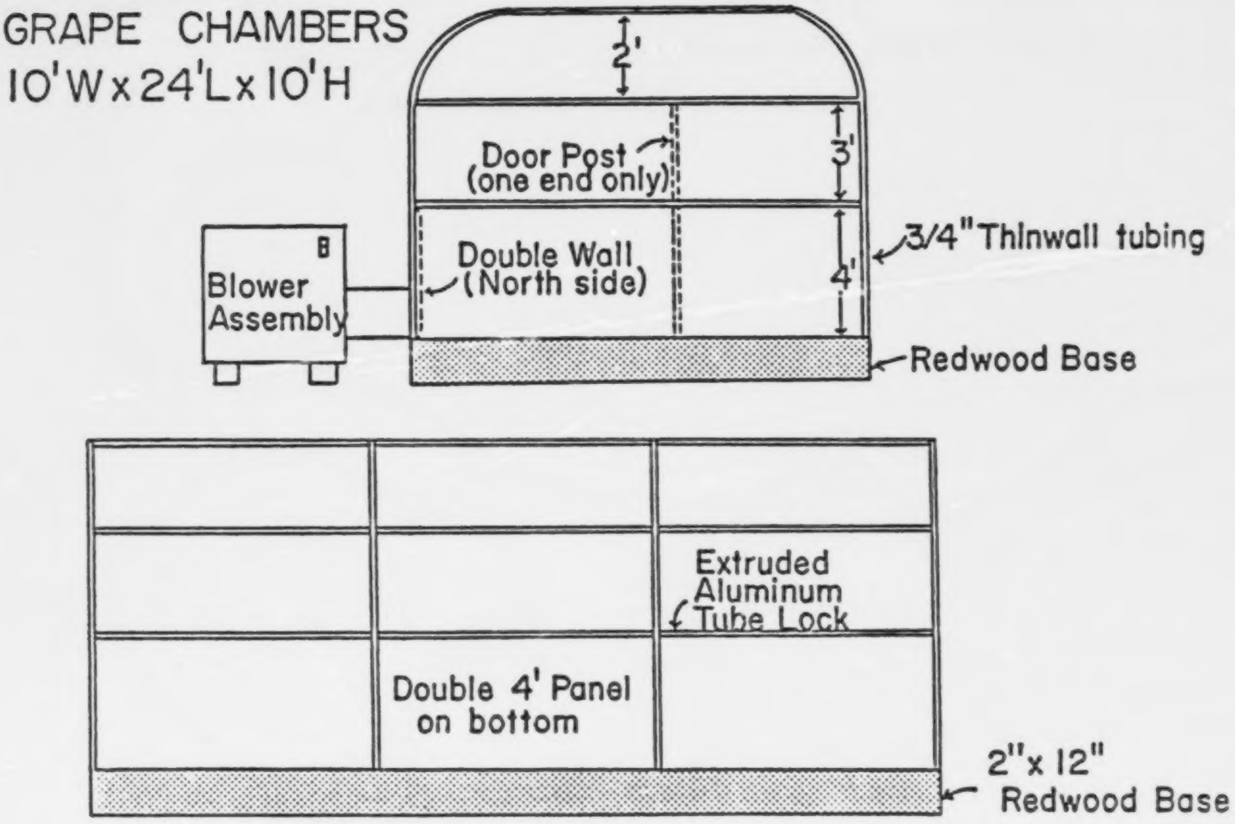


Figure C-2. Schematic diagram of open-top field chamber for grapes (Brewer, 1983).

Publication: Buckenham, A. H., M. A. Parry, C. P. Whittingham, and A. T. Young. 1981. An improved open-topped chamber for pollution studies on crop growth. Environ. Pollut. (Series B) 2:275-282.

Additional Publication: Buckenham, A. H., M. A. J. Parry, and C. P. Whittingham. 1982. Effects of aerial pollutants on the growth and yield of spring barley. Ann. Appl. Biol. 100:179-187.

Location: Rothampsted Experimental Station, Harpenden, England

Summary: An open-top field chamber has been designed and tested for use with grasses. The design is based on wind tunnel tests and incorporates a frustum at the top. The environmental conditions in the chamber are near ambient, but still show detrimental effects on plant growth. A filtered chamber effectively excludes 60-70% of ambient air pollutants.

1. Hardware

a. Chambers

Extensive wind tunnel tests with model chambers of different dimensions have been made to determine the optimum shape and size of the chamber before construction. The chambers are hexagonal, 2.4 m in diameter and 2.3 m high. The frame is horizontal bars of aluminum with vertical aluminum glazing bars. The covering is Novolux sheeting. The area within the chambers is 5.5 m^2, but plants are sampled only from an area 2.5 m^2 between the air dispersion ducts. A frustum inclines at 30° above the horizontal, and a lip projects into the chamber 0.5 m below the frustrum. Large axial flow fans supply 116 m^3 air/min into the chambers. Air entering the filtered chambers passes through a unit containing 16 activated-charcoal filters positioned in parallel. Two flexible ducts connect the filter unit to a set of six rigid ducts arranged in parallel across the floor of the chamber. Air is emitted from 0.01-m diameter holes located 0.03 m apart on both the upper and lower sides of the ducts. Air moves vertically up through the chamber.

b. Pollutant Dispensing and Monitoring

The chamber is used only for ambient air-exclusion studies, pollutants are not added. Ambient SO_2 concentrations are determined with a flame photometric analyzer, sampling at canopy height (up to 0.6 m). Hydrogen fluoride is measured by wet chemistry. Ozone is measured with an UV absorption analyzer.

c. Environmental Control and Monitoring

The environment is not controlled in the chamber. Air temperatures, relative humidty, and light intensity are measured in the chambers and outside.

d. Data Acquisition

Not described.

2. Performance Evaluation

a. Pollutant Uniformity

The filtered chambers exclude 63% of the ambient SO_2, and the unfiltered chambers exclude 8%. Filtered chambers exclude 43% of the ambient HF compared to unfiltered chambers based on fluoride content of barley leaf tissue. There was no information on O_3 distribution in the chambers.

b. Environment Uniformity

Air temperature is 0.5 to 1.4°C higher in chambers than outside. Irradiance is 10 to 20% lower in chambers than outside. Vertical air speed rate through the chamber is 0.25 $m\ s^{-1}$. Relative humidity is reduced 10% from outside.

c. Pollutant Control and Maintenance

At low wind speeds, the filtered chambers greatly reduce SO_2 concentrations; however, with moderate wind speeds SO_2 concentrations in the chamber can be reduced to only 50% of ambient.

d. Environmental Control and Maintenance

The chambers themselves result in altered plant growth compared to outside plots. Barley grown in unfiltered chambers compared to plants from outside have earlier anthesis, fewer shoots per unit area, fewer ears, lower straw dry weights, and a smaller photosynthetic area.

e. Chamber Equilibration

There are 3.5 air exchanges per minute.

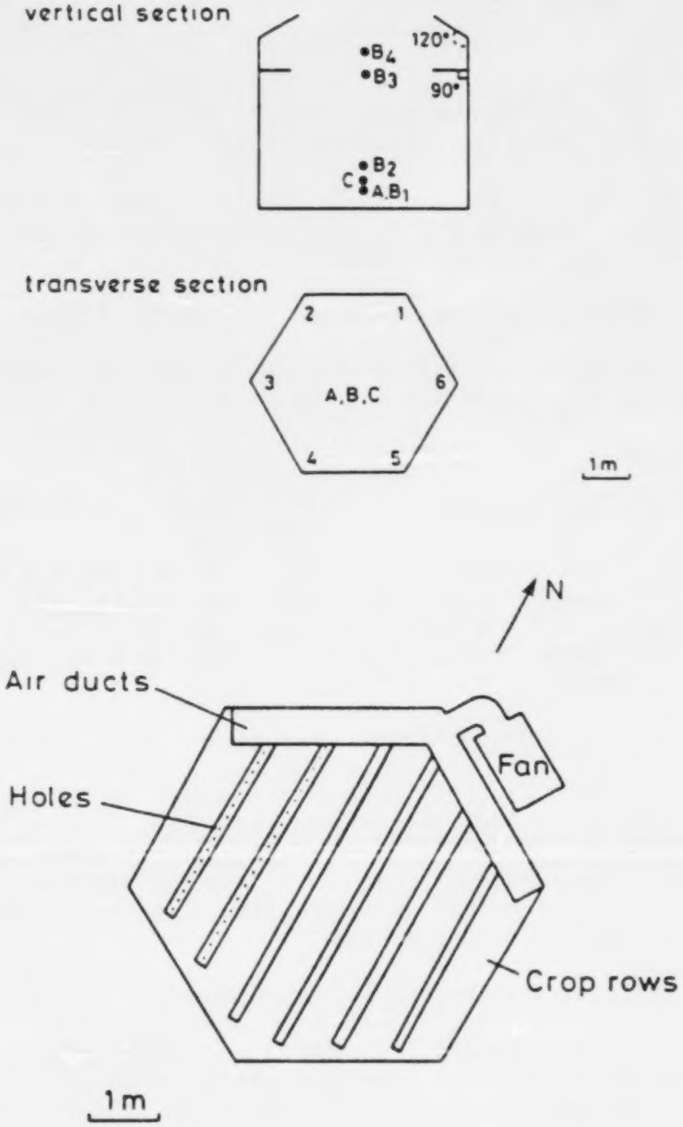


Figure C-3. Schematic diagram of open-top chamber (top), and chamber air dispensing system (bottom) (reprinted from Buckenham et al., 1981, with permission of Elsevier Applied Science Publishers, Ltd.).

Publication: Farrar, J. F., J. Relton, and A. J. Rutter. 1977. Sulfur dioxide and the growth of Pinus sylvestris. J. Appl. Ecol. 14:861-875.

Additional Publications: Garsed, S. G., and A. J. Rutter. 1984. The effects of fluctuating concentrations of sulphur dioxide on the growth of Pinus sylvestris L. and Picea sitchensis (Bong.) Carr. New Phytol. 97:175-189.

Lane, P. I., and J. N. B. Bell. 1984a. The effects of simulated urban air pollution on grass yield: Part I -- Description and simulation of ambient pollution. Environ. Pollut. (Series B) 8:245-263.

Mueller, P. W., and S. G. Garsed. 1984. A microprocessor-controlled system for exposing plants to fluctuating concentrations of sulphur dioxide. New Phytol. 97:165-173.

Location: Imperial College, Silwood Park, Ascot, England

Summary: The facility consists of eight closed-top field chambers used to study the effects of SO_2 and NO_2 on grasses and trees.

1. Hardware

a. Chambers

The chambers are 1.5 x 1.5 m base and 1.0 m high gabled closed-top chambers with a wood base and Perspex® plastic covering. The air inlet is 0.1-m bore tubing at a height of 0.6 m and directed towards the chamber roof. A high capacity fan blows air through the chambers.

b. Pollutant Dispensing and Monitoring

Pollutant dispensing is computer controlled via a microprocessor, flow controllers and valves. Sulfur dioxide was obtained from a tank of 5% SO_2 in nitrogen. Nitrogen dioxide and nitric oxide also are obtained from tanks. Sulfur dioxide is monitored with a flame photometric analyzer, and NOx with a chemiluminescent analyzer and wet chemistry methods.

c. Environmental Monitoring and Controls

The chambers are covered with green plastic netting to absorb visible radiation when used with pine trees. There are no other environmental controls. Temperature is monitored with shielded thermistors and copper-constantan thermocouples, radiant flux with solarimeters, and airflow with an electronic vane anemometer.

d. Data Aquisition

Manual and computer.

2. Performance Evaluation

a. Pollutant Uniformity

Sulfur dioxide concentrations vary by 7 to 15% over time, and by less than 5% between replicate chambers. In a different study, SO_2 and NOx concentrations varied according to an exposure regime representative of central London.

b. Environment Uniformity

The plastic netting absorbed approximately 40% of the visible radiation. The chamber air temperature is 1 to 3°C higher than outside at night, and up to 8 to 10°C higher with bright sunshine during the day. Air temperature varies by ± 0.2°C between chambers in winter, and ± 0.35°C in summer. Vapor pressure deficit was greater in chambers than outside. Air speed through is adequate to provide a boundary layer resistance of 23 to 37 $s\ m^{-1}$ across the chambers.

c. Pollutant Control and Maintenance

The computer control system effectively maintains the SO_2 concentrations at the desired frequency distribution.

d. Environment Control and Maintenance

The environment is different in chambers vs. outside, however, the extent of this variation has been documented.

3. Chamber Equilibration

There are 2 air exchanges per minute.

Publication: Ashmore, M. 1985. Personal communication.

Location: Imperial College, Silwood Park, Ascot, England

Summary: A system of eight small open-top field chambers is being used to study the effects of ambient and filtered air on plants.

1. Hardware

a. Chambers

The chambers have open-tops and are cylindrical, 1.5-m diameter and 1.5-m high. They have aluminum frames covered with clear plastic sheet. Air is supplied from 1.1-kw fans for ambient air and 2.2-kw fans for filtered air; with each fan supplying two chambers. Air enters the chambers through ducting leading to an essentially closed vertical acrylic tube at the side of the chamber. A 0.1-m diameter horizontal polyethylene torus is attached to the vertical tube to bring air around the chamber. The torus has 0.02-m diameter holes punched at 0.15-m intervals. The height of the torus is adjusted upward toward the top of the chamber as the plants develop during the growing season. The amount of air flowing into the chambers is controlled via butterfly valves.

b. Pollutant Dispensing and Monitoring

No pollutants are dispensed; the chambers are used only for ambient and filtered air. Air is sampled for SO_2, O_3, and NO_2 just above the plant canopy.

No environmental control. Methods for environmental monitoring have not been described.

c. Environmental Monitoring and Controls

d. Data Aquisition

Microcomputer system.

2. Performance Evaluation

a. Pollutant Uniformity

The filter efficiency for the chamber is 50 to 60% of ambient SO_2, NO_2, and O_3, but NO is not removed. Pollutant concentrations were not described.

b. Environment Uniformity

Air temperatures are 0 to 2°C higher than outside depending on environmental conditions.

c. Pollutant Control and Maintenance

Not described.

d. Environment Control and Maintenance

Not described.

3. Chamber Equilibration

There are 4 to 5 air exchanges per minute.

Publication: Fowler, D. 1986. Specifications of Open-Top Chambers Used in Barley Studies at the Institute of Terrestrial Ecology. Personal communication, 1986. Also in Proceedings of European Open-Top Chamber Workshop. 1986. Commission of the European Communities. Freiberg, Federal Republic of Germany.

Location: Institute for Terrestrial Ecology, Glasgow, Scotland

Summary: An open-top field chamber system is described for determination of the effects of ambient air pollutants on plant growth. The system is designed to maximize air flow over the plant canopy and can be used for pollutant flux measurements. Fluxes of NO_2, SO_2, CO_2, NO, and O_3 to the canopy have been measured continuously for periods of up to several days, indicating its potential use for linking longer-term (growing season) effects studies to physiological response studies. The system has extensive pollutant and environmental condition monitoring, and computerized data acquisition.

1. Hardware

   a. Chambers

      The chambers are 1.6-m diameter x 1.24-m high cylinders with fiberglass walls. The ground surface area in the chamber is 1.21 m^2 and volume is 1.93 m^3. There is a frustum at the top of the chamber which reduces the top open diameter to 0.9 m. Air is supplied to the chamber from a blower box containing four 0.8 x 0.8 x 0.04 m activated-carbon filters treated with chemicals to absorb NO_2 and SO_2 as well as O_3. Air is pumped into the chamber at a variable rate of 1 to 9 m^3 min^{-1}, but generally with 6 m^3 min^{-1}. Air is distributed within the chamber through a vertically adjustable plastic pipe supplying a perforated, 0.10-m diameter plenum. The plenum generally has been positioned at 0.6 m above the ground.

   b. Pollutant Dispensing and Monitoring

      The chambers have been used only for ambient exclusion studies; pollutants have not been added to the system. Pollutants monitored include SO_2, NO, NO_x, and O_3. Solenoids switch between filtered and ambient chambers every 20 minutes for air sampling; only the average for the last 5 minutes of sampling is saved by the microcomputer system.

   c. Data Acquisition

      Microcomputer system for storage and processing of data; concentrations are summarized in graphical form.

d. Environmental Controls

Environmental conditions are not controlled in the chamber. Air temperature, CO_2 concentration, wind speed, wind direction, and short wave radiation are monitored continuously, stored, and processed by microcomputer. Chemistry of rainfall events is monitored.

2. Performance Evaluation

a. Pollutant Uniformity

The filters remove approximately 95% of the ambient SO_2, 90% of the NO_2, 95% of the O_3, but none of the NO. The exclusion efficiency of the chambers for SO_2, NO_2, and O_3 is approximately 80%, but decreases to 67% with higher ambient wind speeds. Air flow rates into chambers have been adjusted to within 5% between chambers to provide similar pollutant exposures. Concentrations of pollutants are monitored continuously in one filtered and one ambient chamber. Uniformity in pollutant concentrations between all chambers is checked once per month.

b. Environment Uniformity

Air temperature inside the chamber exceeds ambient by < 1°C for short-wave radiation flux of <50 W m^{-2}. For flux between 200-700, the air temperature difference is 1 to 2°C. Leaf temperatures within chambers are only slightly higher than external leaf temperatures. The air speed over the plant canopy is approximately 3 m s^{-1}, resulting in very small temperature differences between chamber air and leaves.

c. Pollutant Control and Maintenance

The pollutant monitoring system has been in continuous operation for over one year.

d. Environmental Control and Maintenance

The environment is similar to ambient year-round, primarily due to the high air speed rate.

e. Chamber Equilibration

There are 10 chamber air exchanges per minute.

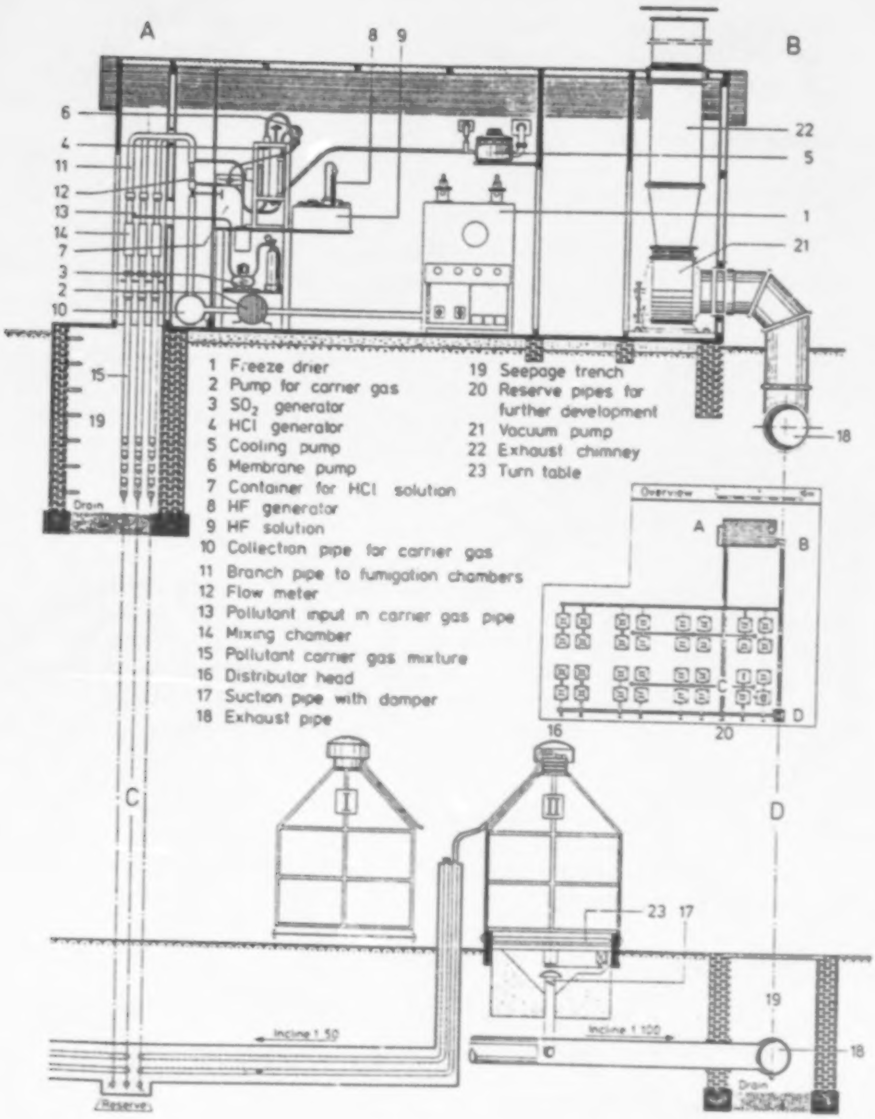


Figure C-4. Diagram of open-top field chamber designed by Institute for Terrestrial Ecology staff (D. Fowler, personal communication). Volume A = 1.21 m^3; B = 0.72 m^3; Flow Rate = 0.10 m^3 sec^{-1}.

Publication: Garrel, J. P. 1986. Personal communication.

Additional Publication: Heagle, A. S., R. B. Philbeck, and W. W. Heck. 1973. An open-top chamber to assess the impact of air pollution on plants. J. Environ. Qual. 2:365-368.

Location: Laboratoire d'Etude de la Pollution Atmospherique, Institut National de la Rechereche Agronomique, Champenoux, France.

Summary: Two open-top field chambers designed to study the effects of gaseous air pollutants on tree seedlings at an altitude of 1000 m in Northeastern France.

1. Hardware

   a. Chambers

      Two chambers were constructed according to the design of Heagle et al. (1973). Each chamber is 2.4 m high, 3.0 m diameter, with an aluminum frame and PVC film covering. The chambers are cylindrical with open tops and no frustrum. The filtered chamber has an activated-charcoal filter which removes SO_2, NO_2, and hydrocarbons, and catalytically converts O_3 to oxygen. The filters do not remove NO.

   b. Pollutant Dispensing and Monitoring

      Pollutants are not added to the chambers; they have only filtered or ambient air. No information is available on pollutant dispensing and monitoring, nor on efficiency in pollutant removal with chamber filtration system.

   c. Data Acquisition

      Not described.

   d. Environmental Control and Monitoring

      The environment is not controlled, and no information is available on any routine environmental monitoring.

2. Performance Evaluation

   a. Pollutant Uniformity

      Not descrited.

   b. Environment Uniformity

      Not described.

c. Pollutant Control and Maintenance

Not described.

d. Environmental Control and Maintenance

Not described.

3. Chamber Equilibration

There are 4 air exchanges per minute.

Publication: Guderian, R. 1977. Air Pollution. Phytotoxicity of Acidic Gases and Its Significance in Air Pollution Control. Ecol. Stud. 22. Springer-Verlag, New York.

Location: Landesanstalt fur Immissionsschutz, Essen, West Germany, Large Gabled Greenhouses

Summary: Large, square, closed chambers have been designed to investigate the effects of SO_2, HF, and HCl on plants. A central building houses instrumentation for taking in ambient air, generating the air pollutants, and delivering them to the chambers via an underground piping system. Polluted air is pumped into the tops of the chambers and mixes in the chamber with filtered air drawn into the chambers.

1. Hardware

a. Chambers

The facility includes 32 large, square chambers with a central peaked roof. The chambers are covered with Mylar polyester film. Outside carrier air enters a central building and goes through a freeze-drier to remove moisture. Sulfur dioxide, HF, and/or HCl are generated in the building and enter the carrier air stream. The polluted air is pumped through underground plastic ducts and enters the chambers through a head manifold at the center of the top of the chamber. Outside air is drawn into the chamber through charcoal-filters by a pump beneath the center of the chamber. A turntable at the base of the chamber rotates the plant pots. The air mixture is then pumped underground, and after washing, exits though an exhaust duct at the top of the control building.

b. Pollutant Dispensing and Monitoring

A comprehensive system is described for generating SO_2, HF, and HCl. Specific pollutant concentrations are produced by regulation of the amounts generated and amount of make-up air used for dilution. The volume of charcoal-filtered ambient air for dilution of added pollutants is regulated by a variable damper in the incoming air stream. Pollutant monitoring is by continuous sampling for SO_2 and HCl and by a wet chemistry method for HF.

c. Environmental Control and Monitoring

Not described.

d. Data Aquisition

Not described.

2. Performance Evaluation

a. Pollutant Uniformity

Not described.

b. Environment Uniformity

Environmental conditions were "slightly altered" from ambient, but specific changes were not described.

c. Pollutant Control and Maintenance

Pollutant control is limited, i.e. of concentrations and exposure times.

d. Environmental Control and Maintenance

Not described.

e. Chamber Equilibration

There are 1.3 to 1.7 air exchanges per minute.

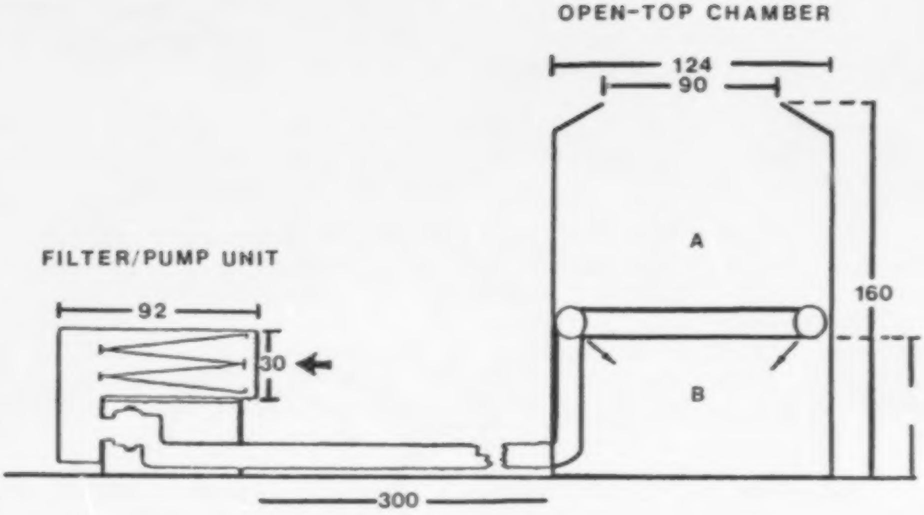


Figure C-5. Diagram of closed field chamber (reprinted from Guderian, 1977, with permission of Springer-Verlag).

Publication: Heagle, A. S., R. B. Philbeck, and W. W. Heck. 1973. An open-top chamber to assess the impact of air pollution on plants. J. Environ. Qual. 2:365-368.

Additional Publications: Davis, J. M., and H. H. Rogers. 1980. Wind tunnel testing of open-top field chambers for plant effects assessment. J. Air Pollut. Contr. Assoc. 30:905-907.

Heagle, A. S, and M. B. Letchworth. 1982. Relationships among injury, growth, and yield responses of soybean cultivars exposed to ozone at different light intensities. J. Environ. Qual. 11:690-694.

Heagle, A. S., and R. B. Philbeck. 1978. Exposure Techniques. In: W. W. Heck, S. V. Krupa, and S. N. Linzon (eds.). Handbook of Methodology for the Assessment of Air Pollution Effects on Vegetation. Air Pollution Control Association, Pittsburgh. pp. 6-1 to 6-19.

Heagle, A. S., R. B. Philbeck, H. H. Rogers, and M. B. Letchworth. 1979. Dispensing and monitoring ozone in open-top field chambers for plant effects studies. Phytopathology 69:15-20.

Heck, W. W., O. C. Taylor, R. Adams, G. Bingham, J. Miller, E. Preston, and L.H. Weinstein. 1982. Assessment of crop loss from ozone. J. Air Pollut. Contr. Assoc. 32:353-361.

Heck, W. W., W. W. Cure, J. O. Rawlings, L. J. Zaragoza, A. S. Heagle, H. H. Heggestad, R. J Kohut, L. W. Kress, and P. J. Temple. 1984. Assessing impacts of ozone on agricultural crops: I. Overview. J. Air Pollut. Contr. Assoc. 34:729-735.

Heggestad, H. E., R. K. Howell, and J. H. Bennett. 1977. The Effects of Oxidant Air Pollutants on Soybeans, Snap Beans, and Potatoes. U.S. Environmental Protection Agency, Corvallis, Oregon. EPA-600/3-77-128.

Olszyk, D. M., T. W. Tibbitts, and W. M. Hertzberg. 1980. Environment in open-top field chambers utilized for air pollution studies. J. Environ. Qual. 9:610-615.

Unsworth, M. H., A. S. Heagle, and W. W. Heck. 1984a. Gas exchange in open-top field chambers. I. Measurement and analysis of atmospheric resistances to gas exchange. Atmos. Environ. 18:373-380.

Unsworth, M. H., A. S. Heagle, and W. W. Heck. 1984b. Gas exchange in open-top field chambers. II. Resistances to ozone uptake by soybeans. Atmos. Envion. 18:381-385.

Weinstock, L., W. J. Kender, and R. C. Musselman. 1982. Microclimate within open-top air pollution chambers and its relation to grapevine physiology. J. Amer. Soc. Hortic. Sci. 107:923-926.

Location: Developed at North Carolina State University with funding from the U.S. Environmental Protection Agency (EPA)

Summary: A detailed description is provided by Heagle et al. (1973) for construction and operation of one of the first open-top field chambers designed for exposures of vegetation to gaseous pollutants in the field. The chamber was adaptable for both pollutant exclusion and addition studies. Tests at multiple sites with many crops indicated the near ambient environmental conditions in the chambers and uniformity of pollutant dispersal. Tests also indicate the usefulness of the chamber for crop loss assessments on a growing season basis. This generic description is applicable to the basic chamber design as tested by a number of researchers. Table C-1 summarizes some basic characteristics of the EPA-designed chamber as it is used by a number of research groups throughout the U.S. and Canada.

1. Hardware

a. Chambers

The chambers are open-top cylinders 2.4 m high x 3.0 m in diameter with an interior plant growing area of 7.1 m^2. The frame is of three rolled-aluminum hoops 1.2 m apart with vertical and oblique aluminum crossbars. The chamber is covered with PVC plastic in separate upper and lower panels. The lower panel is two layers, an inner layer perforated with 250 0.025-m diameter holes, and an outer layer without holes. The lower panel inflates with forced air and acts as a plenum or diffuser. Air flows from the plenum across the plant canopy and out the top of the chamber. The original chamber design ended abruptly at the top of the cylinder, resulting in a turbulent flow of ambient air into the chamber which increased with increasing wind speed. Addition of a conical nozzle or frustum at the top greatly reduces the rate of ambient air incursion, and makes chamber pollutant concentrations more uniform both vertically within the chamber and at different ambient windspeeds (Davis and Rogers, 1980). The frustum is at a 45° angle rising from the top of the chamber resulting in a total chamber height of 2.9 m. This reduces the effective open-top of the chamber to 2.1 m in diameter. Slight modifications of the frustum are often made for the chamber based on local site conditions.

Air is supplied by a 0.63 hp axial-blade fan located in a sheet-metal blower box. The box is equipped with dust-filters and charcoal-filters when supplying filtered air. Air is blown into the chamber at a rate of 70.8 $m^3\ min^{-1}$.

b. Pollutant Dispensing and Monitoring

Pollutant dispensing varies with the chamber installation. A system for dispensing and monitoring O_3 for the chamber has been described in detail by Heagle et al. (1979). Ozone is produced from oxygen with a "silent arc" generator controlled by a timer. Oxygen

Table C-1. Descriptions of EPA-design open-top field chamber facilities at several research sites.

Site	Frustum	# Units	Pollutant Dispensing Mechanism	Data Acquisition	Controlled Environmental Conditions	Reference
North Carolina State U.*	Yes†	110	Computer	Computer	Acid rain Soil moisture Light intensity	Heagle et al. (1973)
Pennsylvania State U.	Yes	39	Computer	Computer	N/I	E. Pell, pers. communication
USDA-Beltsville	Yes	32	N/I	N/I	Soil moisture	E. Lee, pers. communication
Oak Ridge National Lab.	No%	36	Computer	Computer	Acidic rain	Johnston et al. (1986)
Boyce Thompson Institute	Yes	80**	N/I	N/I	Acidic rain	J. Laurence, pers. communication
University of Guelph	No	12	Manual	Manual	N/I	D. Ormrod, pers. communication
U. California, Riverside	Yes	60	Computer	Computer	Acid rain Soil moisture Soil salinity	Temple et al. (1985) D. Olszyk, pers. communication
U. California, Lawrence Livermore Laboratory	Yes	35	Computer	Computer	N/I	K. Surano, pers. communication
Argonne National Laboratory	No	64	Solenoid	Manual	N/I	L. Kress, pers. communication
U.S. Forest Service, Ohio	No‡	12	Computer	Computer	Acidic rain	K. Jensen, pers. communication
Virginia Polytechnic Institute and State University	No	8	Manual	Manual	N/I	W. Winner, pers. communication
University of Minnesota	Yes	27$	Computer	Computer	N/I	Nystrom et al. (1982)

* Currently testing a 4.6-m high chamber for trees.
† Some chambers have additional rain tops.
% Movable cover for acid rain.
‡ Chambers have a rain cap consisting of a 3.7-m wide cone, 0.5 m above the top.
** Twenty of the chambers have plenums of the original Mandl et al. (1973) design.
$ Chamber hardware currently at the University of California, Riverside.
N/I = No information.

flow is adjusted with a pressure regulator, needle valve, solenoid, time clock, and rotameter. Safety switches in the O_3 generator stop the operation automatically if required. Ozone is dispensed from a manifold to individual chambers via rotameters. Pressure is regulated in the manifold to stabilize the rotameters.

Pollutant monitoring (O_3) is via individual air samples drawn through teflon tubing from each chamber through solenoid valves to either a sampling manifold or exhaust manifold by vacuum pumps. Both vacuum pumps exhaust O_3 to the atmosphere through charcoal filters. Sequential activation of the solenoids by a timer (scanner) causes the sample to be delivered to the sampling manifold. Samples are drawn from the sampling manifold by a chemiluminescent O_3 analyzer.

c. Environmental Control and Monitoring

The original EPA chamber has been designed to provide minimal environmental modification but without an initial capacity to control either the atmospheric or soil environment. Stretching polypropylene shade cloth (rated for different degrees of light reduction) across the top of the chamber allows for manipulation of radiation intensity x O_3 interaction studies (Heagle and Letchworth, 1982). Alteration of soil moisture through manipulation of irrigation allows for water stress x O_3 interaction studies (Temple et al., 1985). Placement of the chambers over controlled salinity soil profile plots allows for soil salinity x O_3 interaction studies (D. Olszyk, personal communication). Air flow rate through the chamber can be modified by placing baffles upstream of the fan (Unsworth et al., 1984a,b).

d. Data Aquisition

Data aquisition varies with the installation, but may include manual reduction from recorder charts, or use of a datalogger or interface-computer system for continuous storage of data.

2. Performance Evaluation

a. Pollutant uniformity

Vertical variation in O_3 concentrations is less than 6% of the mean between 0.3- and 1.2-m heights in the chamber. Horizontal variation across the chamber is less than 6, 12, and 14% of the mean at heights of 0.3, 1.2, and 1.8 m. This variation is based on wind speeds less than 4.2 m s^{-1} for a chamber without a frustum (Heagle et al., 1979). At higher wind speeds, uniformity decreases greatly unless a frustum is added. Ambient O_3 exclusion rates ranges from 75% at low wind speeds to 57% at high wind speeds.

b. Environmental Uniformity

Environmental conditions in the chambers vary slightly from outside conditions (Heagle et al., 1973; Heagle and Philbeck, 1978; Heagle et al., 1979; Heggestad et al., 1977; Olszyk et al., 1980; Weinstock et al., 1982). Air temperature generally is $<$ 2°C warmer than outside based on peak temperatures $>$ 32°C. Relative humidity is generally the same as outside, but may be a few percent lower if chamber air tempertures are greater than outside, or slightly higher if air flow is reduced or the chamber contains a great deal of plant material. Irradiance is usually within 85-95% of ambient. Irradiance is decreased with dirty chamber plastic or during spring or fall months with low sun angles. Irradiance can also be temporarily increased with certain sun angles and clean plastic covering. Air movement over the plant canopy at the center of the chamber is approximately 0.6 m s^{-1}. The rainfall pattern inside the chambers varies from outside depending on wind speed.

c. Pollutant Control and Maintenance

The O_3 dispensing and monitoring system of Heagle et al. (1979) performs well over continuous growing season studies. Additional modifications to the original dispensing system, such as feedback control to the O_3 generator via a computer, provide for proportional control of O_3 concentrations as some percentage of ambient (Temple et al., 1985). Computer-control also permits programmed dynamic exposures (Hogsett et al., 1985). Fine tuning of the solenoid system and/or use of critical orifices can further reduce variability in ozone concentrations between chambers and over the growing season (E. Pell, personal communication).

d. Environmental Control and Maintenance

The environmental conditions are similar to ambient (see 2b) at least during the growing season. Maintenance of the plastic film for transparency and the blower for maximum flow rate help keep the chamber environment near outside conditions.

e. Chamber Equilibration

The chamber air exchange rate is approximately 4 chamber volumes per minute.

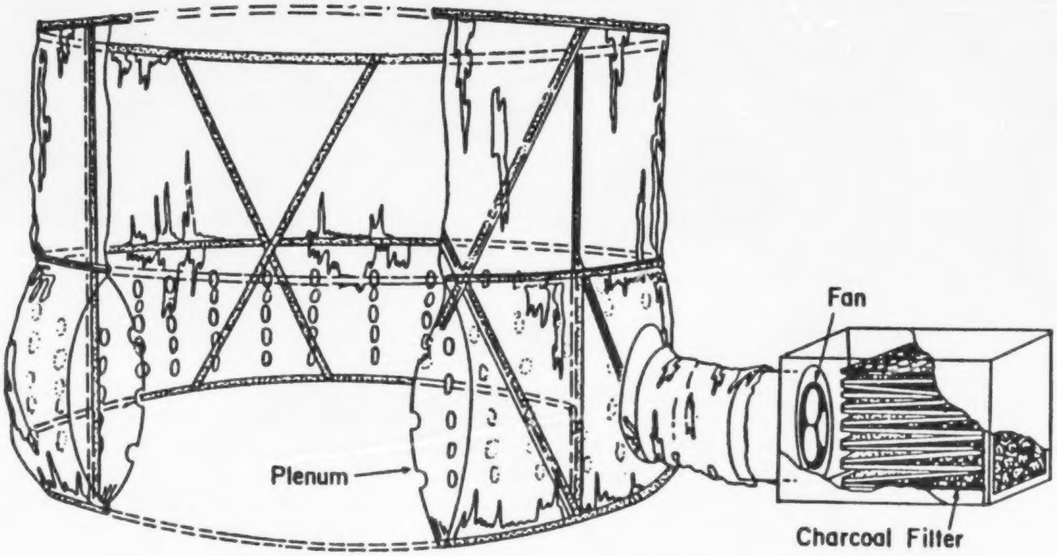


Figure C-6. Diagram of open-top field chamber originally designed by North Carolina State University staff under a contract from the U.S. EPA.

Publication: Hogsett, W. E., D. T. Tingey, and S. R. Holman. 1985. A programmable exposure control system for determination of the effects of pollution exposure regimes on plant growth. Atmos. Environ. 19:1135-1145.

Location: U.S. Environmental Protection Agency, Corvallis, Oregon

Summary: A field exposure facility was designed and constructed to control the atmosphere around the plant canopy for investigations of pollutant dynamics. The chamber is a modification of the Heagle et al. (1973) design with a truncated cone top frustum and a rain cap. The chamber is operated with a microcomputer system which controls pollutant exposures, pollutant and environmental monitoring, and irrigation.

1. Hardware

a. Chambers

The chambers are cylindrical, 3.0 m in diameter and 2.4 m high, with aluminum frames and PVC coverings. A cone-shaped frustum is at the top, reducing the chamber opening to 2.0 m. A 3.0-m diameter rain cap is added 0.3 m above the top to exclude ambient rain. Air flow into the chambers is through charcoal-filters via an axial-blade fan. Airflow into the chambers is 305 m^3 min^{-1}. Air enters the base of the chamber through a 1.2-m high double-walled plenum.

b. Pollutant Dispensing and Monitoring

Ozone is produced by a spark discharge generator using pure oxygen. The desired O_3 exposures are programmed into the computer as hourly concentration values over the 7-month growing season. Up to 14 different exposure profiles can be controlled. The hourly O_3 concentrations are regulated by the microcomputer through feedback control, and O_3 enters the chambers via rotameters. Ozone is sampled sequentially from the chambers and monitored with ultraviolet analyzers.

c. Environmental Control and Monitoring

A microprocessor-controlled drip irrigation system is used for watering and fertilizing the plants. Environmental conditions are monitored in chambers and outside, including air and soil temperature, relative humidity, and irradiance.

d. Data Acquisition

Data acquisition is with an interface and microcomputer. All pollutant dispensing, pollutant and environmental monitoring, and irrigation are controlled by the system. Extensive development of software allows for pollutant episode programming and control.

2. Performance Evaluation

a. Pollutant Uniformity

Hourly-averaged ozone concentrations are within 3 to 13% of the programmed values for all pollutant patterns over the season. Long-term distribution of ozone within the chambers is stable with outside wind speeds of 2.2 to 5.5 m s^{-1}. Ozone concentrations vary by <10% between 0.2 and 0.5 m high in the chamber. Ozone varies by < 15% horizontally across the chamber, except for a few points near the periphery which varied by 20%.

b. Environment Uniformity

The average daily air temperature within the chamber was about 2°C warmer than ambient with the largest variation on cool, sunny days. Daily solar radiation was 13-22% less than ambient during the growing season.

c. Pollutant Control and Maintenance

Pollutant exposure profiles are carefully controlled by this system, in terms of both achieving target levels and between replicate chambers. Weekly span checks are made on analyzers. Sample line loss determined at beginning and end of season.

d. Environmental Control and Maintenance

Not described.

e. Chamber equilibration

There were 1.5 air exchanges per minute.

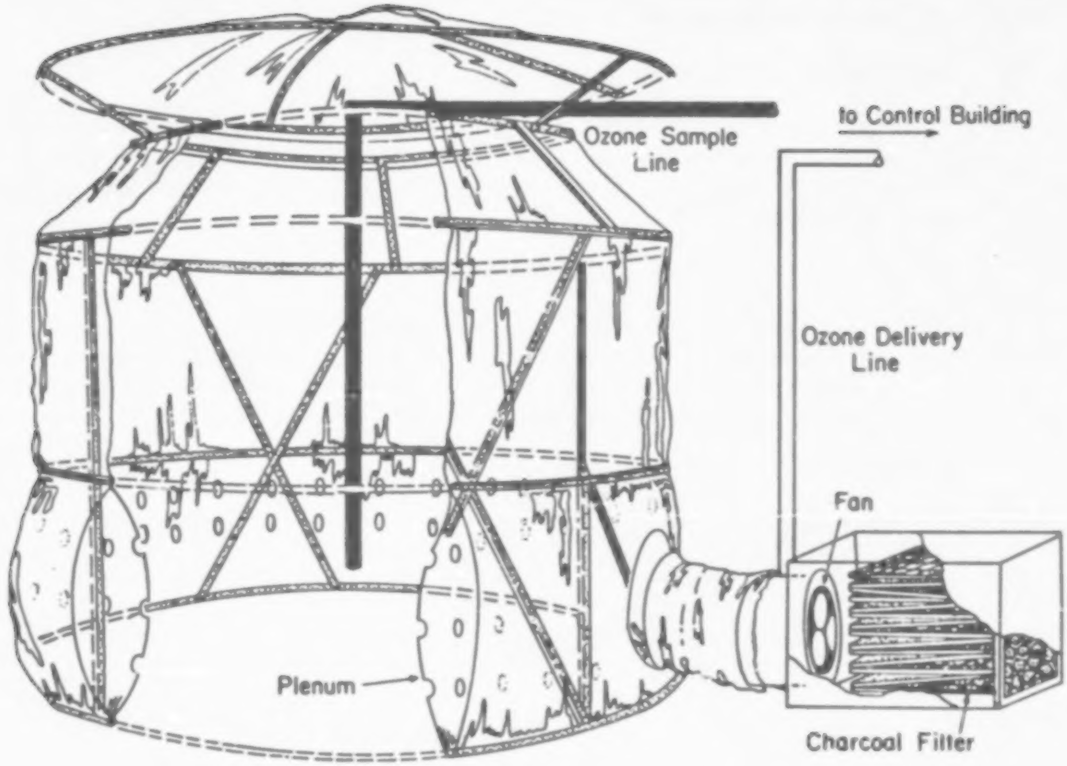


Figure C-7. Diagram of open-top field chamber with rain cap for facility located at the U.S. EPA Environmental Research Laboratory in Corvallis, Oregon (reprinted from Hogsett et al., 1985, with permission of Pergamon Press).

Publication: Kats, G., D. M. Olszyk, and C. R. Thompson. 1985. Open-top experimental chambers for trees. J. Air Pollut. Contr. Assoc. 12:1298-1301.

Location: University of California, Riverside, California

Summary: A large open-top field chamber has been developed for use with young Valencia orange trees for long-term growth and yield studies. The chambers have been used continuously for two years. Ozone and sulfur dioxide concentrations are uniform within and between chambers. Environmental conditions are modified only slightly from ambient; however, these differences are associated with increased growth of trees in the chambers versus outside.

1. Hardware

a. Chambers

The chambers are 2.94 m high and 4.27 m in diameter. Each chamber has a lower base fabricated from two galvanized metal hoops with 10 0.91-m metal uprights and is covered with corrugated fiberglass panels. One fiberglass panel is left unattached and hinged as an entrance to the chamber. The hemispherical domes are fabricated from 10 panels of UVEX plastic which are popriveted together and popriveted and glued with sealant to the upper hoop of the base.

The chambers are equipped 0.61-m height x width x depth blower boxes containing 3/4-hp propeller fan blowers, particulate filters, and corrugated charcoal filters. A 0.53-m diameter x 0.61-m long cylindrical baffle leads from the blower box to the chamber. The baffle contains four crescent-shaped baffles for air mixing. The incoming air flow is directed toward the citrus trees through a sheet metal diffuser containing three vertical and six horizontal rows of 0.076-m diameter holes. Air flow into the chamber is approximately 56 m^3 min^{-1}.

b. Pollutant Dispensing and Monitoring

Sulfur dioxide is dispensed into the chambers via rotameters and a flow controller from a heated tank of pure SO_2. Oxidant treatments are achieved by blocking off part of the air flow through the charcoal filters. Sulfur dioxide is monitored with a pulsed fluorescence analyzer and O_3 with an ultraviolet absorption analyzer. Samples are taken sequentially from chambers with a scanning valve.

c. Environmental Control and Monitoring

The environment is not controlled in the chambers. Air temperature, leaf temperature, relative humidity, and irradiance are measured continuously.

d. Data Aquisition

All pollutant and environmental monitoring is via an interface-microcomputer system.

2. Performance Evaluation

a. Pollutant Uniformity

Filtered chambers effectively exclude 85% of the ambient O_3.

b. Environment Uniformity

Irradiance in the chamber averaged over 90% of outside over a period greater than one year. Leaf temperatures inside chambers averaged 1 to 3°C greater than outside, even with outside temperatures > 40°C. Relative humidity is the same in chambers as outside. Air temperature and dewpoint data are being processed. Air speed within the tree canopy is approximately 0.5 m s^{-1}.

c. Pollutant Control and Maintenance

The chambers provided for good control of pollutant concentrations, effectively excluding ambient air and delivering SO_2 exposures within 10% of the target levels. The major design change over the course of chamber testing is the addition of a pollutant diffuser instead of a baffle. The diffuser is more efficient in providing air flow to the tree canopy than the standard lower chamber plastic duct used in EPA design chambers. The chambers originally were equipped with a 0.91-m diameter duct around the inside of the chamber base. The duct has four horizontal rows of 0.051-m diameter holes, 0.23 m apart. A series of air flow measurements with a grid across the chamber has indicated that air flow across the tree canopy is the same or slightly greater with the metal diffuser than the duct. A diffuser is installed in each chamber as it is simpler to construct and will not deteriorate compared to a plastic duct.

d. Environmental Control and Maintenance

Environmental conditions are uniform between chambers and similar to outside on an annual average basis. However, the differences in environment that did occur resulted in increased vegetative growth for chamber versus outside trees.

e. Chamber Equilibration

There are approximately 1.8 air exchanges per minute.

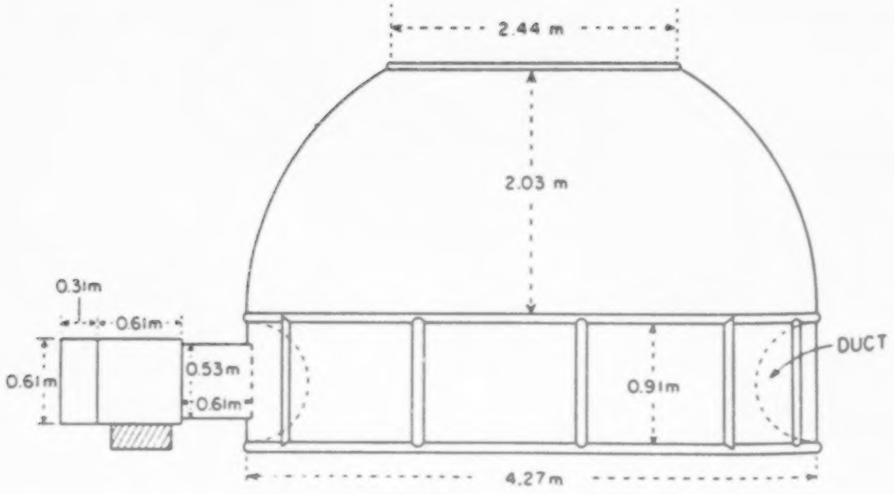


Figure C-8. Diagram of side view of open-top field chamber for citrus trees (reprinted from Kats *et al.*, 1985, with permission of the Air Pollution Control Association).

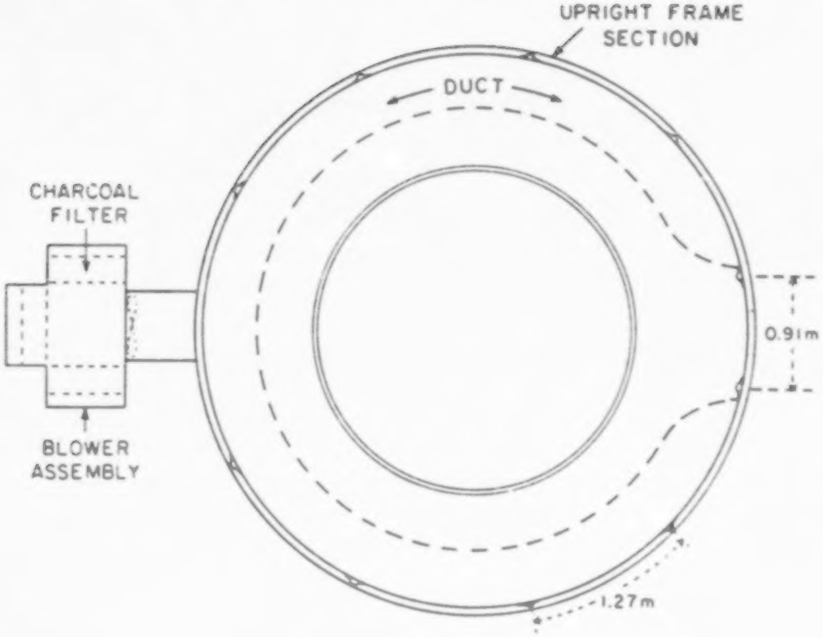


Figure C-9. Diagram of cross-section of open-top field chamber for citrus trees (reprinted from Kats et al., 1985, with permission from the Air Pollution Control Association).

Publication: Keller, T. 1976. Auswirkungen niedriger SO2-Konzentrationen auf junge Fichten. Schweiz. Zeit. Forstwes. 127:237-251. and T. Keller, personal communication.

Location: Swiss Federal Institute of Forestry Research, Birmensdorf, Switzerland

Summary: A description is provided for a large-scale field chamber facility designed for year-round investigations of SO_2 effects on small trees, and recently modified for studies on the effects of O_3. The trees are clonal material growing in 10-liter pots. The site includes 20 round, closed-top chambers and a movable cover to shade plants from full sunlight. The careful control of pollutant exposures within the site is described, and the effect of the chambers on air temperature and relative humidity is documented.

1. Hardware

a. Chambers

The chambers are closed-top cylinders, 2.0 m in diameter and 2.5 m high. The top is not airtight to allow for air flow from the top. The chambers have steel frames and plexiglass walls and tops. Air-flow is from a 50 m^3 min^{-1} capacity blower servicing five chambers, or 10 m^3 min^{-1} per chamber. Studies with SO_2 used ambient air, studies with added O_3 use carbon-filtered air with ambient air controls. A cover over the entire chamber facility provides shade during full sunlight and is controlled by a selenium cell.

b. Pollutant Dispensing and Monitoring

Sulfur dioxide exposures use manual dispensing of tank SO_2, with monitoring by a Philips PW 9700 SO_2 analyzer. Ozone exposures use a Fischer ozone generator supplied with pure oxygen, manually dispensed into filtered chambers at 100 or 300 ug m^{-3} for 9 h day^{-1} (0800-1700), 5 day $week^{-1}$. Ozone is monitored with a Monitor Labs analyzer. For the SO_2 studies, O_3 and NO_x also are routinely monitored, and for the O_3 studies, SO_2 and NO_x are monitored.

c. Environmental Control and Monitoring

Light intensity is controlled by the shade cover to simulate the lower light conditions for young trees of some species. All other conditions are not controlled, but are designed to be as close to ambient as possible.

d. Data Aquisition

Manually by strip-chart recorders.

2. Performance Evaluation

a. Pollutant Uniformity

Not described.

b. Environment Uniformity

Air temperature in chambers is approximately 1 to 5°C higher than outside air depending on month. The difference occurs at night as well as during the day. The difference between chambers and outside tends to be greater in winter than summer. Relative humidity is 1 to 10% lower in chambers than outside during the day. At night, relative humidity reaches 80 to 90% in chambers compared to 100% every night outside.

c. Pollutant Control and Maintenance

The chambers are durable and the dispensing system has provided carefully-controlled exposures over several years.

d. Environmental Control and Maintenance

Light intensity is controlled constantly with a cover operated by a photosensitive cell. The cell is sensitive to changes in sunlight, resulting in repeated changes in light intensity over the day. Over the day, air temperature and relative humidity are more constant in the chambers than outside.

e. Chamber Equilibration

There are 1.5 air exchanges per minute.

Publication: Laurence, J. A., and R. J. Kohut. 1984. Lake Erie Generating Station Grape Study. Phase I and II. Contract #GF127.1T123083. Niagara Mohawk Power Company of the New York State Public Service Commission, Albany.

Additional Publications: Heck, W. W., W. J. Clore, I. A. Leone, D. P. Ormrod, R. M. Pool, and O. C. Taylor. 1985. Multi-Year Research Plan for the Lake Erie Generating Station (LEGS) Grape Study. Vol II. -- Technical Report. State Board on Electrical Generation, Siting, and the Environment, New York Department of Public Service, Albany.

Mandl, R. H., J. A. Laurence, and R. J. Kohut. 1987. Development and testing of new open-top chambers for exposing large perennial plants to air pollutants in the field. Phytopathology. In Press.

Location: Boyce Thompson Institute, Ithaca, New York

Summary: Two new designs of open-top field chambers have been developed for exposures of grapevines to air pollutants. One design is a modified cylindrical chamber enlarged to 4.6-m diameter x 3.7-m high. The other is a modification of the rectangular grapevine chamber (Brewer, 1983). The objectives of the designs are to enclose grapevines trained to an umbrella system, to provide uniform distribution of pollutants through the grapevine canopy, to minimize intrusion of ambient air, and to minimize environmental modification.

1. Hardware

   a. Chambers

      The chamber designs are based on extensive testing of models in a wind tunnel. The cylindrical chamber is 4.6 m in diameter x 3.7 m high with a frustum reducing the open top by 50% and baffles between the frustrum and top of the cylinder. The rectangular chamber is 7.3 m long x 2.7 m wide x 3.7 m high with a frustum, baffles and wind-actuated louvers at the top. Both chamber designs have aluminum frames and PVC coverings. A blower equipped with charcoal filters pumps air into a PVC plenum around the lower one-third of the chambers (1.2 m high).

   b. Pollutant Dispensing and Monitoring

      The chambers have been tested with the addition of O_3 and HF gases, but no information is given on dispersion or performance. Ozone was monitored with a Teco® analyzer and HF was measured by wet-chemistry.

c. Environmental Control and Monitoring

The environment is not controlled in the chambers. Irradiance, rainfall, and leaf temperature are measured inside the chambers and outside by LICOR® sensors, rain gauges, and leaf thermocouples, respectively.

d. Data Acquisition

Acquisition of monitoring data is done on a time-sharing system.

2. Performance Evaluation

a. Pollutant Uniformity

Ozone and HF concentrations vary horizontally in the chambers by up to 33%. In general O_3 concentrations in the rectangular chambers are lowest at the blower end and at 0.6 and 1.8 m above ground at the opposite end of the chamber. Flux of HF is uniform throughout chambers. The pollutants vary by 10-100% vertically in the chambers between heights of 1.8-3.1 m.

b. Environment Uniformity

Irradiance is reduced by up to 30% in the cylindrical chambers and 50% in the rectangular chambers compared to outside. Irradiance distribution is not uniform within either chamber design, but is especially variable in the rectangular chambers. There is a substantial rain shadow effect with both types of chambers. Rain is 10-15% of ambient at the north ends and 50-70% of ambient at the center. Mean air temperature differences are 2.5°C higher in the chambers compared to the outside, however, leaf temperatures occasionally are as much as 9°C higher in the chambers compared to outside.

c. Pollutant Control and Maintenance

Both types of chambers are effective in excluding ambient oxidants. Based on the wind tunnel test, the circular chamber is designed with a 50% frustum which minimizes incursion of ambient air from the top. The rectangular chamber is designed with louvers in addition to baffles and frustum to further decrease ambient air incursion.

d. Environmental Control and Maintenance

The environment is modified from ambient and is variable within chambers.

e. Chamber Equilibration

Not described.

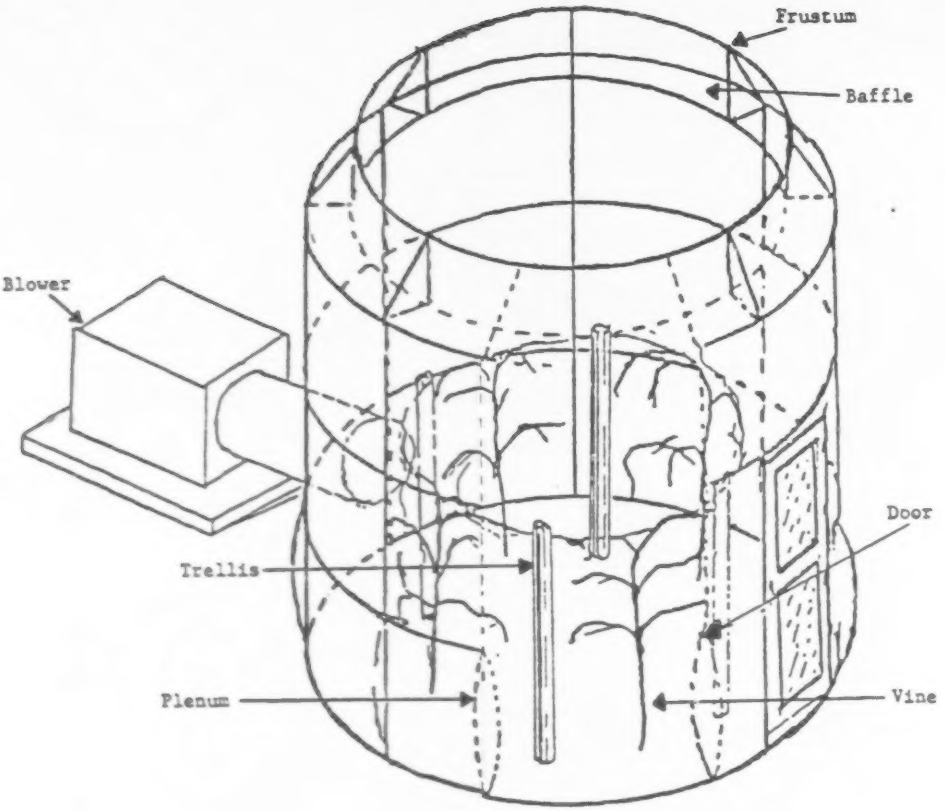


Figure C-10. Schematic diagram of large cylindrical open-top chamber for grapevines (Laurence and Kohut, 1984).

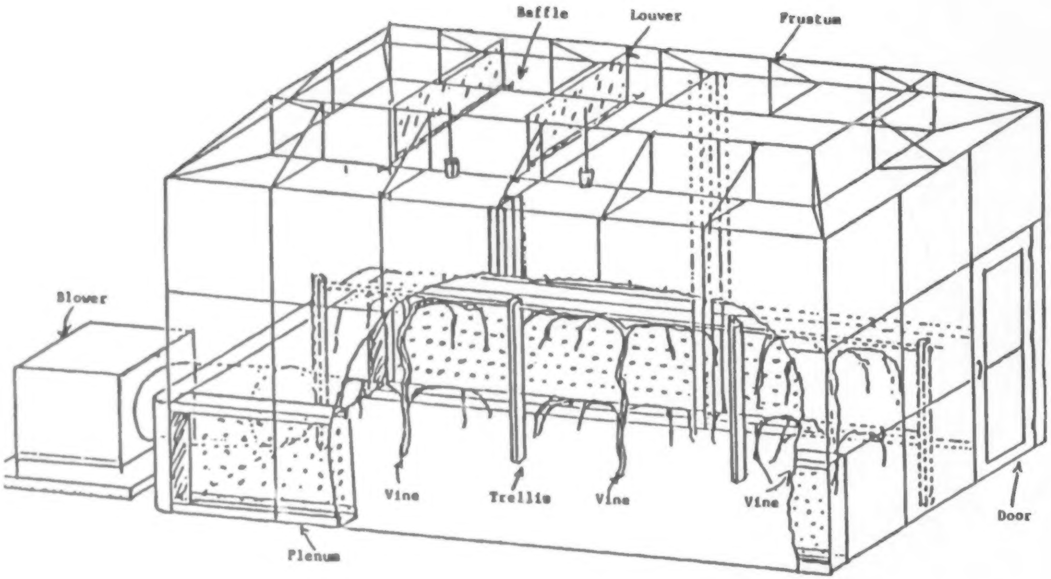


Figure C-11. Schematic diagram of rectangular open-top field chamber for grapevines (Laurence and Kohut, 1984).

Publication: Lucas, P. 1985. Hemispherical Domes for Fumigation of Plants. University of Lancaster, United Kingdom. Personal communication.

Location: University of Lancaster, Lancaster, England

Summary: A facility with eight large closed dome chambers was designed, constructed, and tested for studies with SO_2, NO_2, and O_3 air pollutants.

1. Hardware

a. Chambers

There are eight chambers, each 4.6 m in diameter, and 2.0 m high for a volume of 20 m^3. The frame is anodized aluminum with glass panels. The plant growing area is 12.6 m^2. The air handling system operates by both pushing air into the dome and pulling air from it. A large fan pumps 1700 m^3 min^{-1} through ducts and large charcoal-filters to four domes. Pollutants are added via 0.59-m diameter tubes in the mixing-chamber immediately before the air enters the domes. After mixing, polluted air at a flow rate of 280 m^3 min^{-1} enters each chamber via a horseshoe-shaped duct around the inside of the base of the dome. Resistance of the system reduces the air flow through the dome to 40-60 m^3 min^{-1}. Polluted air is pulled through the chamber by a central fan mounted at the top of the dome center and exhausted to the outside.

b. Pollutant Dispensing and Monitoring

Ozone is generated from dry air by electrical discharge and is dispensed to the chambers via a manifold and rotameters. Pure SO_2 is fed through a rotameter and diluted with compressed air before entering chambers via a manifold and rotameters. Nitrogen dioxide comes from a heated tank of pure NO_2 maintained at 35°C, with control valves and rotameters maintained at 40°C.

c. Environmental Control and Monitoring

Large capacity cooling units have been added to reduce summer temperatures to outside levels. Other environmental factors are not controlled.

c. Data Acquisition

The system is being computerized.

2. Performance Evaluation

a. Pollutant Uniformity

Ozone concentrations vary by < 10% around the perimeter of the chamber and at the center.

b. Environment Uniformity

Air temperatures in the chambers average 3 to 5°C warmer than outside. Relative humidity in the chambers generally is $< 2\%$ less than outside. Irradiance is approximately 80% of ambient. Air speed around the perimeter of the dome averages 0.9 m s^{-1}, and 0.18 m s^{-1} at 0.15 m above the ground in the center of the dome. Leaf boundary layer resistance is estimated at 0.09 s cm^{-1} around the perimeter of the dome based on filter-paper model leaf measurements.

c. Pollutant Control and Maintenance

Pollutant levels are uniform and the center of the chamber is chosen as an acceptable sampling location. Weekly span checks are made for the O_3, SO_2, and NO_2 analyzers; and weekly zero checks are made for the SO_2 and NO_2 analyzers. All analyzers are calibrated monthly.

d. Environmental Control and Maintenance

The possibility exists that the large surface area of the duct absorbs heat, contributing to the increase in internal air temperature vs. outside. A coating of reflective paint has been proposed to correct this problem. The center of the dome is not used for growing plant material due to the low air speed.

e. Chamber Equilibration

There are 2 to 3 air exchanges per minute.

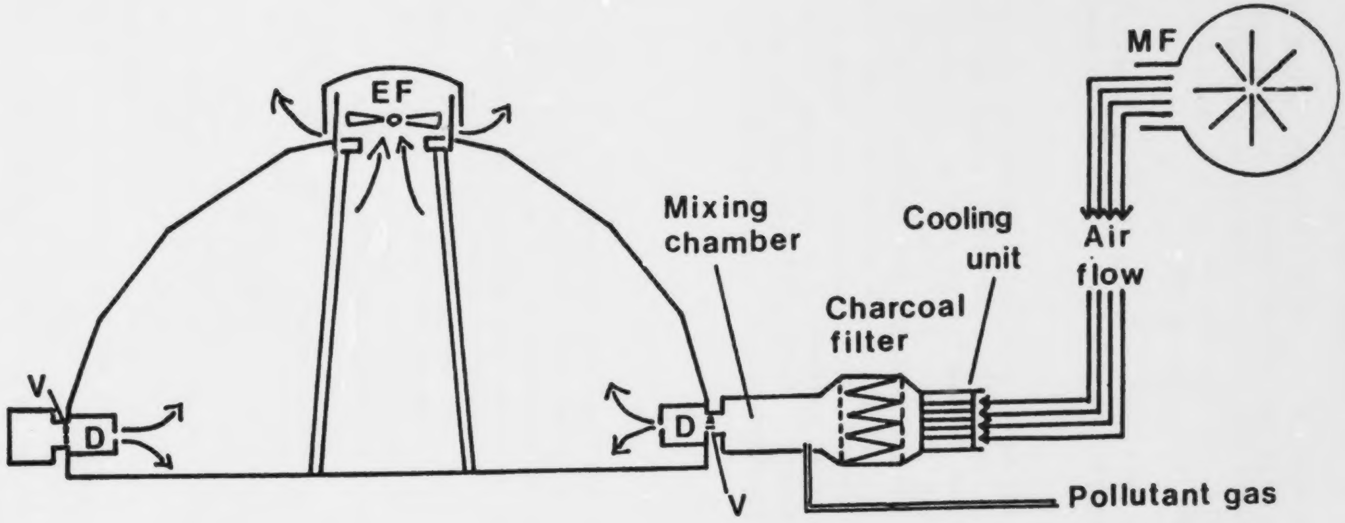


Figure C-12. Schematic diagram of dome chamber designed by University of Lancaster staff (P. Lucas, personal communication, 1986).

Publication: Mandl, R. H., L. H. Weinstein, D. C. McCune, and M. Keveny. 1973. A cylindrical open-top field chamber for exposure of plants to air pollutants in the field. J. Environ. Qual. 2:371-376.

Additional Publication: McCune, D. C., D. C. MacLean, and R. E. Schneider. 1976. Experimental approaches to the effects of airborne fluoride on plants. In: T. A. Mansfield (ed.). Effects of Air Pollutants on Plants. Society for Experimental Biology Seminar Series, Vol. 1. Cambridge University Press, Cambridge. pp. 31-46.

Location: Original design developed at Boyce Thompson Research Institute, Ithaca, New York. Chambers of the same design are located at Riverside, California.

Summary: A detailed description is provided by Mandl et al. (1973) for construction and operation of the other early open-top field chambers designed for exposures of vegetation to gaseous pollutants in the field. The chamber is adaptable for both pollutant exclusion and addition studies. Features different from the EPA chamber include fiberglass covering, an adjustable plenum for air dispersion, and a different design for the air handling system. Tests indicate near ambient environmental conditions in the chambers, uniformity of pollutant dispersal, and flux of HF to plants in the chamber. Tests also indicate the usefulness of the chamber for oxidant-exclusion studies on a growing season basis.

1. Hardware

a. Chambers

The chambers are open-top cylinders 2.4 m high x 2.74 m in diameter with an interior plant growing area of 5.9 m^2. The frame is of three rolled aluminum hoops 1.2 m apart dividing the chamber horizontally into two separable modules for different heights of plants. The chamber is covered with corrugated fiberglass panels attached to the hoops with nylon nuts and bolts. There are upper and lower panels. A donut-shaped PVC plenum, 8.53 m long x 0.20 m outside diameter, is attached to the inner wall of the base of the chamber. The plenum is perforated with 0.025-m diameter holes at 0.076-m intervals, oriented to direct the air stream horizontally and toward the center of the chamber. Air flows from the plenum across the plant canopy and out the top of the chamber. The original chamber design ended abruptly at the top of the cylinder, resulting in turbulent flow of ambient air into the chamber which increased with increasing wind speed. Addition of a baffle at the top of the chamber greatly reduces the rate of ambient air incursion, and makes chamber pollutant concentrations more uniform both vertically in the chamber and with different ambient windspeeds (Kats et al., 1976). The base of the baffle is 0.10 m from the side of the chamber, rising at a 45° angle 0.6 m to just above the top of the chamber. The original chamber design has a polypropylene yarn netting (0.016-m mesh) stretched over the top.

Air is supplied by a 0.75-hp nonoverloading blower located in a sheet metal blower box mounted on a trailer. The box is equipped with dust filters and charcoal filters when supplying filtered air. Air is blown into the chamber at a rate of 28.3 m^3 min^{-1}.

b. Pollutant Dispensing and Monitoring

The original chambers have been used for ambient oxidant effects studies and HF studies. No added ozone and HF are supplied to the chambers by volatilization of aqueous HF solutions. Oxidants are measured with Mast Ozone analyzers and HF by wet chemistry.

c. Environmental Control and Monitoring

The environment is not controlled in the chamber. Air temperature and relative humidity are measured by spot checks during the day, but frequency and methods are not described.

d. Data Acquisition

Data aquisition is manual.

2. Performance Evaluation

a. Pollutant Uniformity

Fluoride accumulation indicates that pollutant concentrations vary vertically by 63% from 0.15 m to 1.2 m high in the chamber. Horizontal variation is 7 to 15% across the chamber. Oxidant exclusion is 60 to 70% of ambient. No gradient evaluation for ozone given.

b. Environment Uniformity

Environmental conditions in the chambers vary slightly from ambient (Heagle et al., 1978; Mandl et al., 1973). Air temperature generally is < 2°C warmer than outside based on peak temperatures > 90°C. Relative humidity is generally the same as outside. Irradiance is usually within 70-95% of outside in free sunlight. Yellowing of the chamber fiberglass and low sun angles of spring and fall decreases irradiance. Air movement over the plant canopy in the chamber center is approximately 0.24 m s^{-1}.

c. Pollutant Control and Maintenance

Dynamic sampling methods of gas concentrations in the air indicate that concentrations within chambers can be relatively uniform across chambers (7 to 15% variabiltiy) (McCune et al., 1976). However, flux measurements for HF show that the actual flux of pollutants can vary considerably within chambers due to differences in air flow rates across chambers. Thus increasing the uniformity of air flow in the chambers is desirable to equalize fluxes. Within the lower 1.2 m of the chamber, flux is most uniform when the air is blown at a 45° angle up and away from the plenum. Other modifications of flow direction and pattern are suggested to provide a vertical pollutant flux profile specific for different types of plant canopies.

d. Environmental Control and Maintenance

The environment modification in the chambers is uniform over summer growing seasons but can change as the fiberglass yellows with age. The mesh top does not exclude ambient rain; however, the amount of rain is still less in the chamber than outside depending on angle of incidence.

e. Chamber Equilibration

The air exchange rate is 2 per minute.

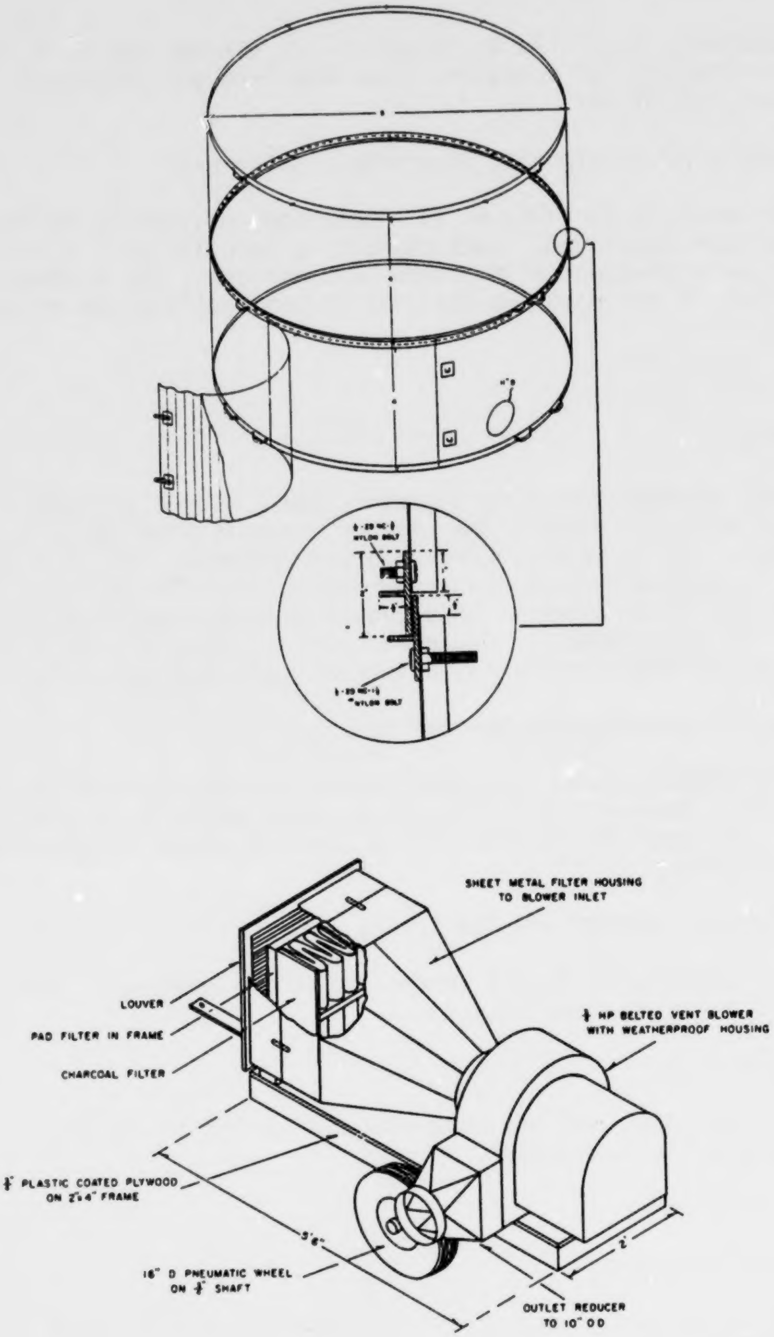

NYLON BOLT
NYLON BOLT
SHEET METAL FILTER HOUSING TO BLOWER INLET
LOUVER
PAD FILTER IN FRAME
CHARCOAL FILTER
¼ HP BELTED VENT BLOWER WITH WEATHERPROOF HOUSING
¾" PLASTIC COATED PLYWOOD ON 2"x4" FRAME
5'6"
2'
16" D PNEUMATIC WHEEL ON ¾" SHAFT
OUTLET REDUCER TO 10" OD

Figure C-13. Construction details for open-top field chamber (top) and blower assembly (bottom) (reprinted from Mandl et al., 1973, with permission of Soil Science Society of America).

Publication: Musselman, R. C., P. M. McCool, R. J. Oshima, and R. R. Teso. 1986. Field chambers for assessing crop loss from air pollutants. J. Environ. Qual. 15:152-157.

Location: University of California, Riverside, California

Summary: A field exposure facility of 18 closed-top, octagonal, teflon-covered chambers has been developed. Each chamber is supplied with filtered air, ambient air, or a gradient of filtered plus ambient. The chamber provides precise control of pollutant levels with slight modification of the environment.

1. Hardware

   a. Chambers

      Each chamber is 2.5 in diameter, and 2.4 to 2.1 m high (top tapers diagonally down). The chamber frame is aluminum with teflon covering. Air is supplied from two 5-hp blowers. Air from one blower is pulled through charcoal filters; nonfiltered air goes through the other blower. Underground ducting leads from both blowers to each chamber. The amounts of filtered and nonfiltered air are adjusted with a butterfly damper at each chamber outlet.

   b. Pollutant Dispensing and Monitoring

      The chambers have been used primarily with filtered and nonfiltered air. However, O_3 or SO_2 can be added manually at each chamber inlet. Air sampling is done with a scanning valve interface-microcomputer system.

   c. Environmental Control and Monitoring

      The environment is not controlled in the chambers. Air temperature and irradiance are measured.

   d. Data Aquisition

      All pollutant and environmental monitoring is via an interface and microcomputer.

2. Performance Evaluation

   a. Pollutant Uniformity

      Pollutant distribution has been determined with CO as a test gas. Both horizontal CO concentrations and vertical (0.3 to 0.9 m high) concentrations vary by < 2%.

b. Environment Uniformity

Irradiance averaged 11% lower in chambers than outside after three years of chamber use. Chamber air temperatures were 2-4°C warmer than outside during the day, and varied < 1-1.5°C across chambers.

c. Pollutant Control and Maintenance

Pollutant concentrations are very uniform in the chambers and independent of ambient wind speed.

d. Environmental Control and Maintenance

The environment is relatively uniform within and among chambers.

e. Chamber Equilibration

The number of air exchanges per minute is adjustable.

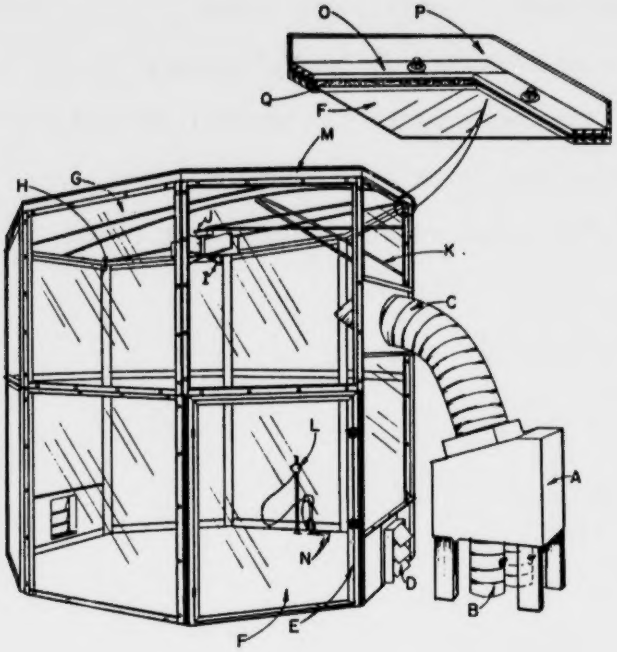


Figure C-14. Field exposure chambers. A. Air inlet mixing box. B. Air inlets from filtered and nonfiltered blowers with butterfly valves to adjust flows. C. Aluminum inlet duct to chamber from mixing box. D. Louvers for air-exiting chamber. E. Chamber door. F. Teflon film on chamber wall. G. Chamber teflon top panel. H. Aluminum conduit post for attaching wall panels. I. Impellor. J. Impellor motor and mount. K. Impellor support frame. L. Pollutant air sample tube. M. Chamber top frame support. N. Thermocouple sensor. O. Aluminum bar to secure teflon film to aluminum angle. P. Aluminum wall frame. Q. Weather strip (reprinted from Musselman et al., 1986, with permission from Soil Science Society of America).

Publication: Semi-open-top chambers for use in remote, high-wind areas. D. Olszyk, personal communication; and P. Miller, personal communication.

Location: University of California, Riverside, California. The chambers have been operated at the Tanbark Flats Experimental Forest, San Gabriel Mountains, California; Daggett, California in the Mojave Desert; Sequioa National Park, California; and at the University of Geneva, Switzerland.

Summary: The chamber is a smaller, modified version of the Heagle *et al.* (1973) chamber developed for use with small shrubs and trees. The chamber has been used to expose whole shrubs of *Larrea tridentata*, a desert perennial (D. Olszyk, UCR, personal communication), and *Ceanothus crassifolius*, a chaparral perennial from Southern California (A. Bytnerowicz, UCR, personal communication). The chamber also has been used for multiple seedlings of conifer species both in Sequoia National Park and in Switzerland at the University of Geneva (P. Miller, USFS, Riverside, personal communication). The chamber has a closed top with four holes, leaving approximately 40% of the surface area open.

1. Hardware

The chambers are 2.0 m in diameter x 2.5 m high cylinders modified from the design of Heagle *et al.* (1973). The surface area in the chamber is 3.1 m^2. Each chamber is covered with clear polyvinylchloride film. The top has four 0.68-m diameter holes accounting for 40% of the surface area. The semi-open top is required, since a totally open-top design is physically unstable under the high wind speed conditions that can occur in the desert. Air is blown into the chambers at a rate of at least 0.31 m s^{-1} from a 1/5-hp high pressure blower.

b. Pollutant Dispensing and Monitoring

For the *Larrea*-SO_2 studies the air is filtered to remove any confounding ozone, since ambient air contained little SO_2 at this site. Sulfur dioxide is metered into the incoming chamber air stream from a tank of approximately 100% SO_2 enclosed in an insulated galvanized steel can. Sulfur dioxide is monitored with a pulsed fluorescent analyzer. For the *Ceanothus* or conifer oxidant studies, filtered or ambient air is blown into the chambers with or without added O_3 from a generator. Ozone was monitored with a scanning valve system and UV analyzer. Both SO_2 and O_3 concentrations are controlled with rotameters.

c. Environmental Control and Monitoring

The environment is not controlled in these chambers. Environmental conditions, including irradiance, temperature, and humidity are measured inside chambers and outside on an intermittant basis.

d. Data Acquisition

Data acquistion is by strip-chart recorders.

2. Performance Evaluation

a. Pollutant uniformity

Not described.

b. Environmental Control and Maintenance

Air temperatures in the chambers are 1 to 5°C warmer than outside, with the largest differences at ambient air temperatures > 32°C. The chambers reduce irradiance, but the decrease has not been determined.

c. Pollutant Control and Maintenance

Not described.

d. Environmental Control and Maintenance

The chamber air temperature can increase significantly above ambient, possibly altering plant response to air pollutants. Photosynthesis is affected by the chamber itself in *Larrea*, likely due to the increased air temperature. The chamber top prevents wind incursion which can be especially significant in the desert and other open areas. The top also helps alleviate damage at high wind speeds by channeling the air over the chamber.

e. Chamber Equilibration

There are at least 2 chamber air volumes exchange per minute.

Publication: Roberts, T. M., R. M. Bell, D. C. Horsman, and K. E. Colvill. 1983. The use of open-top chambers to study the effects of air pollutants, in particular sulphur dioxide, on the growth of ryegrass Lolium perenne L. Part I. Characteristics of modified open-top chambers used for both air-filtration and SO_2-fumigation experiments. Environ. Pollut. 3:9-33.

Additional Publication: Colvill, K. E., R. M. Bell, T. M. Roberts, and A. D. Bradshaw. 1983. The use of open-top chambers to study the effects of air pollutants, in particular sulphur dioxide, on the growth of ryegrass Lolium perenne L. Part I. The long-term effect of filtering polluted urban air or adding SO_2 to rural air. Environ. Pollut. (Series A) 31:35-55.

Location: University of Liverpool, Liverpool, England

Summary: A low exposure chamber has been designed, tested, and used for exposing grasses to filtered vs ambient air, and assessing the effects of added SO_2. The chamber design meets two objectives: small size, and divides the air flow so that filtered air passes over the grasses and out through the base and top of the chamber. The chamber has a duct around the top to blow air across the plant canopy. The chamber is used in year-round studies which have indicated that SO_2 has detrimental effects in the winter and spring, but not the summer.

1. Hardware

a. Chambers

Four chambers have been constructed, with a 1.3-m diameter, 0.7-m high cylinder, originally covered by PVC film. The PVC was replaced by fiberglass after one year. A split air inlet channels approximately 80% of the air at 0.5 $m^3 s^{-1}$ into a collar with a PVC strip duct inside the upper margin of the chamber. Air is directed through 0.0025-m diameter holes at an angle over the plant canopy. The other 20% of the inlet air passes across a flow corrector to insure laminar flow. An exhaust fan slightly less powerful than the inlet fan, pulls air out of the chamber. In two chambers the air is filtered with a 1.0 x 0.3 x 0.1 m block of activated charcoal. In the two ambient chambers the charcoal block has been replaced with a polystyrene baffle to produce an equal distribution of air at the inlet.

b. Pollutant Dispensing and Monitoring

For filtered vs ambient air studies, there is no controlled pollutant dispensing. Controlled levels of SO_2 are added to chambers from a tank of pure SO_2 fed through a rotameter and diluted with compressed air in a stainless steel mixing chamber. The SO_2 is injected into the inlet ducts between the fan and the polystyrene baffels. Monitoring of SO_2 is with a flame photometric analyzer.

c. Environmental Control and Monitoring

Environmental factors are not controlled. Detailed measurements of air temperature, light intensity, relative humidity, and rainfall are made in chambers and outside. Air speed over the canopy is checked periodically with a hot-wire anemometer.

c. Data Aquisition

Data acquisition is manual.

2. Performance Evaluation

a. Pollutant Uniformity

The air flow pattern effectively excludes ambient with a cone of air blown upwards and inwards from the chamber edge to minimize ambient air incursion. Air is also passed over the grass canopy and out through a ventilation fan at the rear of the chamber. The seasonal mean added SO_2 levels vary by 60%. Exclusion of SO_2 in the filtered vs ambient chambers has averaged 56% over a 3-year period. Unfiltered chambers have SO_2 levels 93% of outside concentration. Sulfur dioxide concentrations varied by < 20% horizontally across the unfiltered chambers, and up to 50% across chambers with added SO_2.

b. Environment Uniformity

Irradiance is 15-25% lower in chambers than outside. At low temperatures, the air is 1 to 2°C warmer in chambers than outside. Continuous air movement over the canopy prevents hoarfrost on leaves. When outside air temperatures are above 10°C, it is similar in the chambers. There is no appreciable difference in relative humidity between chambers and outside plots. Rainfall in chambers is similar to outside plots. Air flow over the grass canopy is 0.5 to 0.8 $m\ s^{-1}$. The chambers caused a 29% reduction in early summer plant growth, but had no effect on winter growth. There is some evidence for greater SO_2 flux to plants in ambient chambers versus outside, based on total sulfur content.

c. Pollutant Control and Maintenance

The main disadvantage of these smaller chambers is the reduced ambient pollutant filtering efficiency compared to larger chambers (Heagle _et_ _al_., 1973).

d. Environmental Control and Maintenance

The chamber has the advantage of a reduced rain shadow, and laminar flow of air across the plant canopy instead of turbulent flow up through the chamber as found in larger open-top chambers.

e. Chamber Equilibration

There are 6 to 7 air exchanges in the chamber per minute.

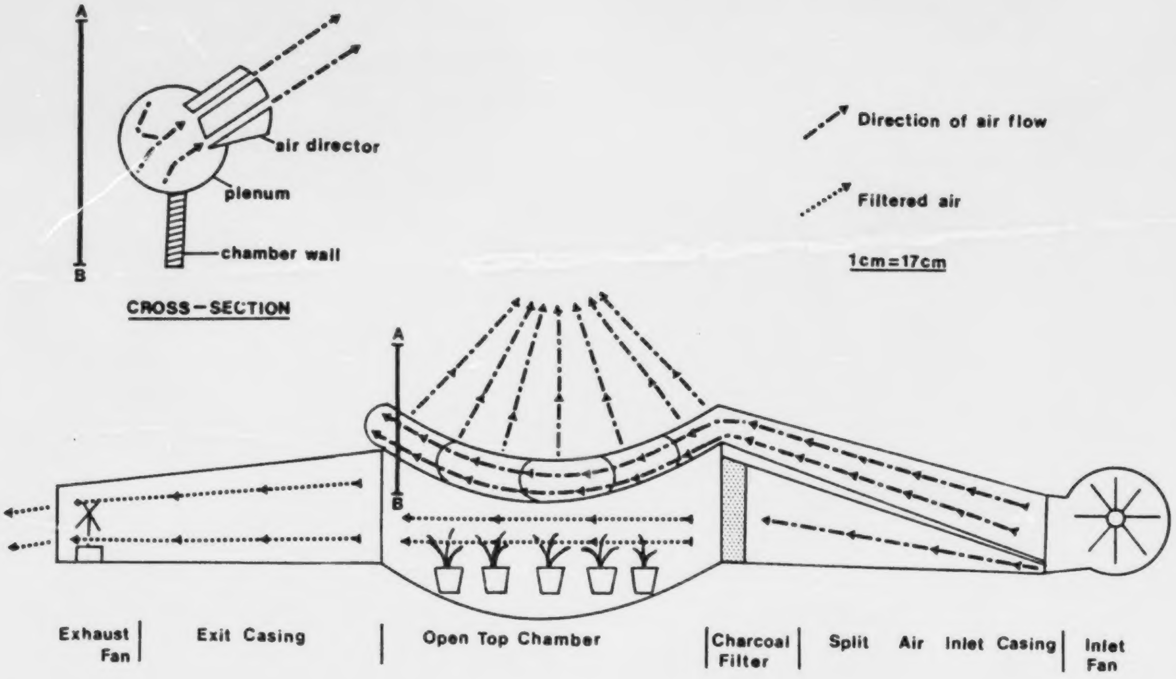


Figure C-15. Schematic diagram of low open-top field chamber for grasses (reprinted from Roberts et al., 1983, with permission of Elsevier Applied Science Publishers, Ltd.).

Publication: Roberts, T. M. 1981. Effects of stack emissions on agriculture and forestry. CEGB Research July:11-24.

Location: Central Electricity Research Laboratories, Leatherhead, England

Summary: Four large chambers have been constructed by Central Electricity Generating Board research staff for air pollution studies. The 4.0-m diameter dome-shaped chambers are designed to provide close control of pollutant concentrations with minimal environmental variation compared to outside. Chamber air flow is designed to ensure that gas flux rates to plants are similar to outside. The air flow and pollutant injection rates are computer-controlled to simulate concentrations of gas mixtures that can occur around electrical generating stations.

1. Hardware

   a. Chambers

      The four chambers are 4.0-m diameter closed-domes with a volume of 30 m^3 and floor area of 9 m^2. The frame is aluminum and the covering is glass. Air is blown into each chamber through an underground duct by a 5-hp fan which sucks air through a charcoal-filter with surface area of 15.8 m^2. Air at a flow rate of 120 m^3 min^{-1} enters the chamber through the center of the bottom. The flow is pointed toward a diffuser near the top of the chamber which directs the air down over the plant canopy.

   b. Pollutant Dispensing and Monitoring

      Pollutants are injected into the incoming air stream past the fan. Monitoring is through a timesharing device. All pollutant dispensing and monitoring is computer controlled.

   c. Environmental Controls

      Environmental conditions are not controlled. Air and soil temperatures, irradiance, and relative humidity are recorded by computer.

   d. Data Acquisition

      All data acquisition is computerized.

2. Performance Evaluation

   a. Pollutant Uniformity

      Not described.

b. Environment Uniformity

Irradiance is approximately 25% lower in the chambers than outside. Daily air temperature is increased by approximately 0.7°C across a range of outside temperatures from -2 to +23°C. The cumulative degrees temperature over the winter are 10% greater in chambers than outside. The daily soil temperature is 1°C higher in the chamber than outside except for cold still periods when the soil temperature is lower in the ventilated chambers than outside. Relative humidity is lower in the chambers than outside with high humidities (> 80%), but 10% higher at lower outside humidities (60%). The air flow rate over the plant canopy is approximately 0.5 m s^{-1} at canopy height.

c. Pollutant Control and Maintenance

The charcoal filters remove approximately 90% of ambient SO_2 and O_3, and 75% of ambient NO_2. Charcoal filters which have been operated over the winter released 100 ppb NO in the spring and early summer with specific high temperature conditions.

d. Environmental Control and Maintenance

The chamber produces modifications in climatic conditions which are comparable to those of open-top field chambers. The relative humidity differences in chambers vs ambient also occurred when plants were not present, indicating that charcoal filters were probablly releasing moisture during the day and retaining it during the night.

e. Chamber Equilibration

There are 4 air exchanges per minute.

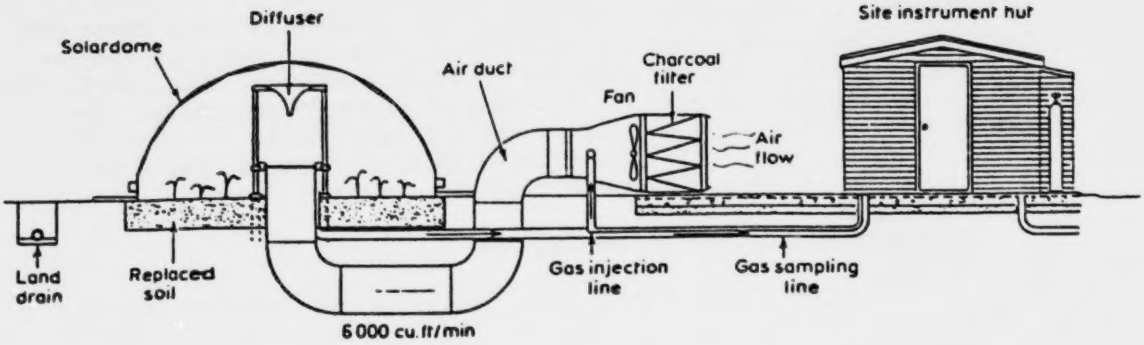


Figure C-16. Schematic diagram of dome chamber designed by staff of the Central Electricity Research Laboratory, Leatherhead, England (Roberts, 1981).

Publication: Runeckles, V. C., L. M. Staley, and N. R. Bulley. 1978. A downdraft chamber for studying the effects of air pollutants on plants. Can. J. Bot. 56:768-778.

Location: University of British Columbia, Vancouver, British Columbia

Summary: A conical exposure chamber is described for gaseous air pollutant exposures. The blower is located on the top of the chamber, providing a downdraft of charcoal-filtered air and/or added polllutants to the plant canopy.

1. Hardware

   a. Chambers

      The chamber is 4.9 m high, 1.2 m diameter at the top, and 2.4 m diameter at the bottom. The base of the chamber is 0.4 m above the soil. The chamber frame is steel pipe, with five hoops of sequentially smaller diameter from bottom to top, and four side tubes. The chamber is covered with PVC and held in place by guy wires. The blower is in a box supported by the top steel hoop. It contains a rain cover, dust filters, activated-charcoal filters, and a fan providing 127 m^3 min^{-1} down through the chamber.

   b. Pollutant Dispensing and Monitoring

      Ozone is produced by a Grace generator and injected into the chamber immediately below the fan. Ozone is monitored with colorimetric and chemiluminescent monitors.

   c. Environmental Control and Monitoring

      The environment is not controlled in this system. Wind speed, irradiance, net radiation, relative humidity, and air and soil temperatures are measured in chambers and outside to characterize the environmental modification by the system.

   d. Data Acquisition

      Not described.

2. Performance Evaluation

   a. Pollutant Uniformity

      Ozone concentrations vary by 6 to 8% across the chamber, and < 5% vertically between heights of 0.2 and 1.0 m within the chamber. When ambient O_3 concentrations are low, filtering the chamber excludes 40% of ambient O_3 under calm conditions, and 25% of the O_3 under windy conditions. With higher ambient O_3 exclusion is 70% of ambient.

b. Environment Uniformity

The wind speed is 0.5 m s^{-1} vertically downward, at a position in the center of the chamber 0.3 m above the soil surface. The transmittance of the PVC is 90 to 93% of ambient irradiance. On clear days irradiance is the same in chambers as outside, however, it is 30% lower on cloudy days. Net radiation loss is negative outside at night, but is 0 in the chamber due to lack of reradiation to the sky. Air and soil temperatures are usually < 1°C warmer in the chamber than outside. Relative humidity is 10% less in chambers than outside.

c. Pollutant Control and Maintenance

The chamber is useful for providing a pattern of air dispersion over the plant canopy under representive conditions. Pollutant distribution within the chamber is essentially uniform. The air-exclusion capability of the chamber is least efficient for areas with relatively low air pollutant concentrations.

d. Environmental Control and Maintenance

Environmental conditions in the chamber are similar to outside, with the largest difference in relative humidity. The variability in chamber conditions is similar to ambient variability.

e. Chamber Equilibration

Not described.

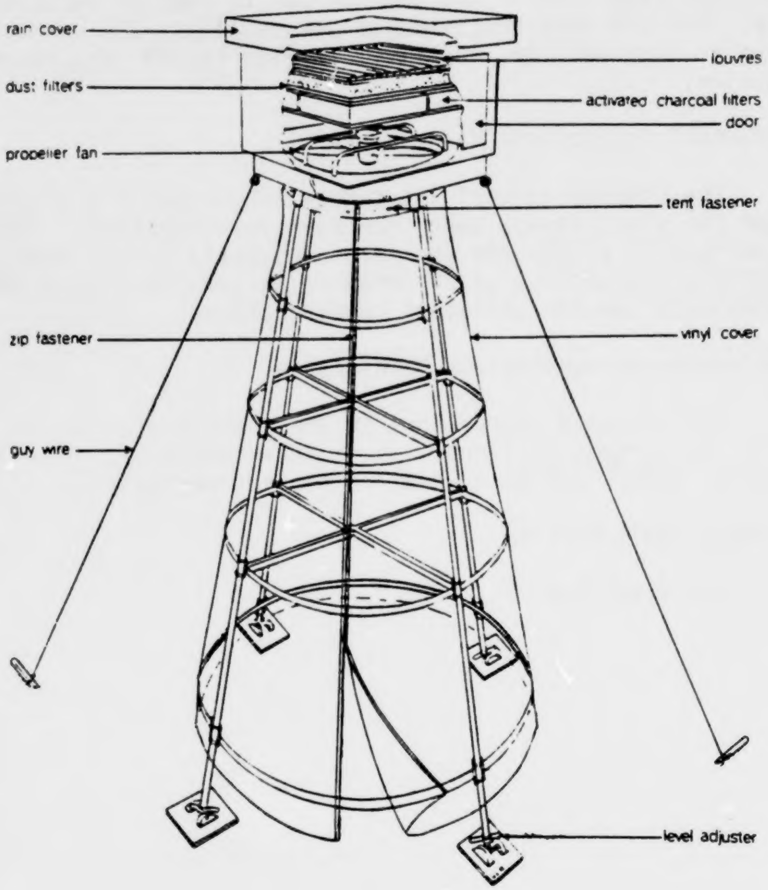


Figure C-17. Schematic diagram of downdraft chamber for field studies (reprinted from Runeckles et al., 1978, with permission of Canadian Journal of Botany).

Publication: Seeliger, T., A. Wichmann, J. Schweckendiek, and R. Bornkamm. Personal communication. 1985.

Location: Technical University of Berlin, Berlin, Germany

Summary: Equipment has been designed, constructed, and tested to simulate ozone exposures. The equipment consists of one open-top chamber and a computer-controlled system for dispensing pollutants, monitoring, and data aquisition. The chamber has been characterized for vertical and horizontal ozone distribution.

1. Hardware

a. Chambers

The chamber is eight-sided, 2.5 m in diameter, and 2.4 m high. The chamber has an aluminum frame, teflon covering, and no frustum. The lower part of the chamber is double-walled, with air entering around seven sides of the chamber through the perforated teflon wall. Air is supplied from a blower at 42 m^3 min^{-1} via ventilator, dust filters, activated charcoal filters, and turbulator before entering chamber.

b. Pollutant Dispensing and Monitoring

Ozone is supplied from a generator and monitored by an ultraviolet photometer.

c. Environmental Control and Monitoring

The environment is not controlled in the chamber; however, five environmental conditions are monitored.

d. Data Aquisition

A datalogger and microcomputer monitor air pollution concentrations and environmental variables. The microcomputer also controls O_3 dispensing based on a programmed episode.

2. Performance Evaluation

a. Pollutant Uniformity

Ozone concentrations varied by 28% horizontally across the chamber which had a turbulator in the inlet duct to mix the air. Air varied by 14% vertically between 0.2 and 1.75 m above the bottom of the chamber.

b. Environment Uniformity

Not described.

c. Pollutant Control and Maintenance

The system simulates episodic air pollutant events. Asymmetrical O_3 concentrations were measured vertically and horizontally in the chamber.

d. Environmental Control and Maintenance

Not described.

e. Chamber Equilibration

There are 3.5 air exchanges per minute.

Publication: Skarby, L. 1986. Personal communication.

Location: Swedish Environmental Research Institute, Gothenburg, Sweden

Summary: Open-top field chambers have been designed and operated to study effects of O_3 on pine and spruce trees.

1. Hardware

   a. Chambers

   Ten cylindrical open-top field chambers were constructed based on the design of Heagle et al. (1973). The chambers are 2.5 m high, 3.0 m diameter, with aluminum frames and PVC plastic (hard) coverings. The chambers have 45° frustra, reducing the top diameter to 1.25 m. Air flow (40 m^3 min^{-1}) driven by an axial-blade fan enters the base of the chamber through a 0.4-m circular tube manifold with 0.025-m diameter holes distributed to give an even air flow inside the chamber.

   b. Pollutant Dispensing and Monitoring

   Ozone (0.22 ppm from 2300 to 0600) is dispensed into one chamber from a Sonozaire electric discharge generator. The O_3 is dispensed into the chamber through a 0.4-m diameter, 2.5-m long manifold duct. Ozone is monitored with a chemiluminescent analyzer and NO_x with a fluorescent analyzer. A microcomputer controlled the monitoring of air pollutants with a solenoid valve system. Frequency of monitoring is not described.

   c. Environmental Control and Monitoring

   The environment is not controlled in the chambers. Air temperature is routinely monitored with platinum resistance temperature detectors. Humidity is measured with a psychrometer or a Pitot tube.

   d. Data Acquisition

   Microcomputer system.

2. Performance Evaluation

   a. Pollutant Uniformity

   Ozone concentrations vary by less than 10% horizontally across the chambers. Vertical distribution is not described.

   b. Environment Uniformity

   The average daily temperature in the chamber was a maximum of 4°C warmer than ambient.

c. Pollutant Control and Maintenance

Sample line loss was determined at the beginning and end of exposure period, but the results were not described.

d. Environmental Control and Maintenance

Not described.

3. Chamber Equilibration

There are 2 to 3 air exchanges per minute.

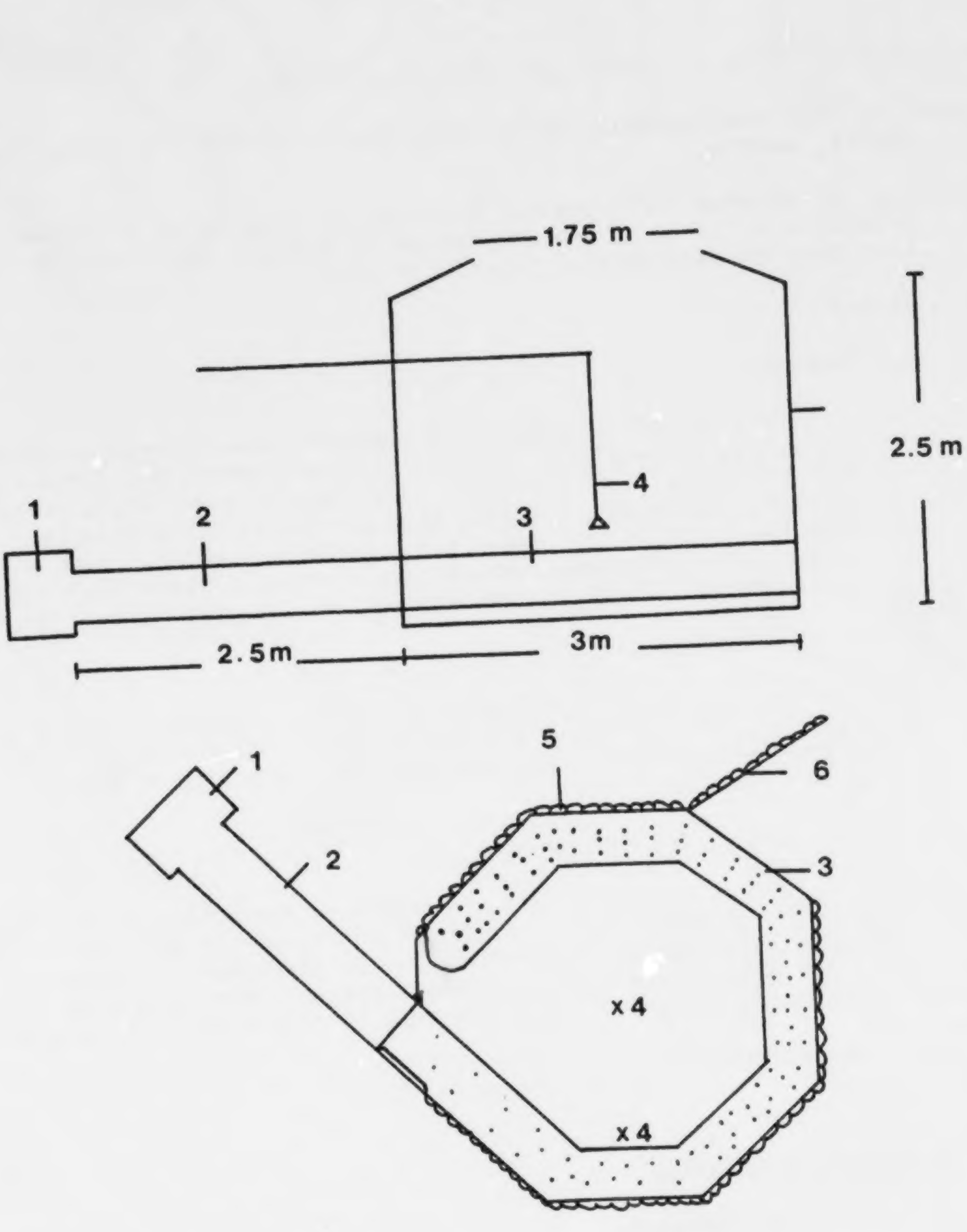


Figure C-18. Schematic diagram of open-top field chamber for air pollutant exposure in Gothenburg, Sweden: (1) fan; (2) duct; (3) plenum (manifold); (4) ozone/NO_x measurements; (5) PVC corrugated hard plastic; (6) Door (Skarby, Personal communication, 1986).

Publication: Soja, G. 1986. Personal communication.

Location: Austrian Research Centre Seibersdorf, Institut fur Landwirtschaft, Vienna, Austria

Summary: An open-top field chamber facility was constructed to evaluate effects of filtered or nonfiltered air to plants. Wheat and red clover have been the experimental material to date.

1. Hardware

   a. Chambers

      Cylindrical open-top field chambers were constructed based on the design of Heagle _et al_. (1973). The chambers are 2.4 m high, 3.0 m diameter, with a frustum that rises to a 45° angle above the chamber, effectively reducing the open-top to 1.5 m diameter. Air is dispensed within the chamber via a perforated plastic tube around the inner wall. Filtered chambers have charcoal filters which remove approximately 97% of the ambient NO_2 and SO_2, but none of the NO.

   b. Pollutant Dispensing and Monitoring

      Pollutants are not dispensed into the chambers -- there are only filtered and nonfiltered air treatments. Sulfur dioxide is monitored with a pulsed fluorescence analyzer, NO_x is monitored with a fluorescent analyzer.

   c. Data Control and Monitoring

      The environment is not controlled in the chambers. Air temperature, leaf temperature, relative humidity of the air, and irradiance are measured periodically with a Lambda Instruments Corporation LI-COR 6000 portable photosynthesis system. Air speed also is checked periodically. Soil moisture is determined with tensiometers.

   c. Data Acquisition

      Manual.

2. Performance Evaluation

   a. Pollutant Uniformity

      Not described.

   b. Environment Uniformity

      Not described.

c. Pollutant Control and Maintenance

Not described.

d. Environmental Control and Maintenance

Not described.

3. Chamber Equilibration

Not described.

Publication: Thompson, C. R., and D. M. Olszyk. 1985. A Field Air-Exclusion System for Measuring the Effects of Air Pollutants on Crops. EPRI EA-4203. Final Report for Project 1908-3. Electric Power Research Institute. Palo Alto, California.

Location: University of California, Riverside, California

Summary: The facility consists of 20 open-top field chambers constructed according to the basic shape and design of the Heagle et al. (1973) chamber, but with a top baffle instead of a frustum and permanent supporting posts instead of a movable aluminum frame. The facility was constructed for, and is maintained under a contract with the California Air Resources Board. The chambers modify the plant growing environment to a similar extent as the Heagle et al. (1973) chambers. The chambers have been used for year-round studies with a variety of crop and native plant species.

1. Hardware

a. Chambers

The 20 chambers follow the basic design and shape described by Heagle et al. (1973)., chamber except that the installation is not portable and the chambers can not be removed for field planting of crops. The chambers are cylinders 2.43 m high and 3.0 m in diameter with rolled aluminum frames covered by PVC film. The upper half of the chamber has a single layer of film and the lower half has a double layer. The inner layer is covered with 0.03-m diameter holes, positioned in six rows, with 0.15 between holes and rows. The chamber has a cone-shaped baffle at the top (Kats et al., 1976) that reduces the top hole diameter to 1.5 m. Each chamber is equipped with a 1.52-m long x 0.6-m wide x 0.6-m high blower box containing a fiberglass particulate filter, corrugated activated charcoal filter, and 3/4-hp ILG propeller blowers. The chambers have side posts buried 0.15 m in the ground, and below ground air sampling, pollutant delivery, and irrigation systems. The chambers have been used both with potted plants and plants planted in the ground.

b. Pollutant Dispensing and Monitoring

The pollutant delivery system includes a Griffin ozone generator, and heated, insulated containers for tank gases such as sulfur dioxide and nitrogen dioxide. The output of the tank gases is controlled by a mass flow controller. The concentrations of all gases added to individual chambers are controlled by individual rotameters.

c. Environmental Controls and Monitoring

The environment in the chambers has not been controlled in past studies. Recently, humidity variation has been added to determine its effect on the sensitivity of plants to air pollutants. A propane-fired boiler provides dry steam, a water-softening system provides water, a humidity delivery system has been installed in two chambers, and long ducts deliver the steam to chambers with enough mixing time to allow for any condensation prior to entry into the chambers. A humidistat controls steam injection into the chamber ducts. Dew point and air temperature sensors determine chamber humidity, and a computer feedback system is being developed to control the humidistats based on ambient and chamber humidities and desired humidity set points.

When completely modified, the chamber apparatus will be able to measure air, soil, and leaf temperatures, relative humidity, irradiance, and air speed.

d. Data Acquisition

Pollutant concentrations in chambers are determined with a scanning valve system associated with O_3, SO_2, or NO_2 analyzers. Pollutant concentrations and environmental conditions are recorded, stored and processed with an interface-microcomputer system.

2. Performance Evaluation

a. Pollutant Uniformity

Pollutant concentrations vary by < 2% between 0.05 and 0.41 m vertically in the chambers. Horizontal concentrations have not been determined. Concentrations of added pollutants vary by < 10% over time based on growing-season averages of hourly data.

b. Environment Uniformity

Air speed is approximately 0.6 m s^{-1} over the plant canopy. Air temperature generally is < 1°C warmer in the chambers than outside, but can range up to 4°C warmer, especially in cooler months. Soil temperatures are up to 3°C warmer than outside at depths of up to 0.10 m. Leaf temperatures are cooler than outside in early morning and up to 3°C warmer than outside during mid-day. Irradiance is still within 75% of ambient after more than two years use of the PVC vinyl chamber covering. At mid-day during the summer, chambers have 3 to 4% higher relative humidities than outside.

c. Pollutant Control and Maintenance

Pollutant concentrations can be effectively controlled in the chambers. The chambers exclude approximately 75 to 80% of ambient O_3.

d. Environment Control and Maintenance

Not described.

e. Chamber Equilibration

There are approximately 2 air exchanges per minute.

Publication: Van Haut, H. 1972. Test methods to prove phytocidal pollutants. Environ. Pollut. 3:123-132.

Location: Landesanstalt fur Immissionschutz, Essen, West Germany

Summary: Small, closed plexiglass chambers have been designed and used for studies on the effects of ambient air pollutants on small seedling plants. Each experimental unit consists of two chambers, one with filtered air and the other with ambient air. The chambers are self-contained units with individual air and water supply.

1. Hardware

   a. Chambers

      Each chamber is a 0.6 x 0.9 x 0.9 m closed plexiglass box. The air supply system consists of an elevated air intake, charcoal filter, and exhaust blower. Air flow is from the filter, into the top of the chamber, through a top baffle, down through the chamber, and pulled out through the system by an exhaust fan. The filtering material is coated with silver and silver oxide to remove SO_2, HF and HCl. A watering system continuously supplies the plants through a closed system with water reservoir and pump.

   b. Pollutant Dispensing and Monitoring

      No dispensing occurs in the chambers and there is no information on monitoring.

   c. Environmental Control and Monitoring

      Not described.

   d. Data Aquisition

      Not described.

2. Performance Evaluation

   a. Pollutant Uniformity

      The single pass-through system and top baffle disperses ambient or filtered air through the system. No information is provided concerning pollutant uniformity between systems.

   b. Environment Uniformity

      Not described.

c. Pollutant Control and Maintenance

The air filter is successful in removing ambient pollutants based on studies with BEL W3 tobacco as a bioindicator plant.

d. Environmental Control and Maintenance

Not described.

e. Chamber Equilibration

Not described.

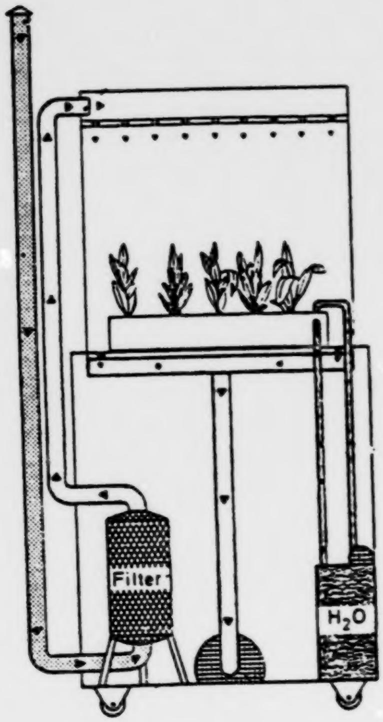


Figure C-19. Gaseous exposure chambers (reprinted from Van Haut, 1982, with permission of Elsevier Applied Science Publishers, Ltd.).

APPENDIX D

Descriptions of Facilities and Performance Evaluations -- Outdoor Chambers for Gaseous Dry and Wet Deposition Research

Publication: Ashmore, M. R. 1986. Personal communication.

Additional Publication: Ashmore, M. R., J. N. B. Bell, and C. Dalpra. 1980. Visible injury to crop species by ozone in the United Kingdom. Environ. Pollut. (Series A) 21:209-215.

Location: Imperial College, Silwood Park, England

Summary: An open-top field chamber was designed to investigate the effects of ambient air pollutants on crops.

1. Hardware

   a. Chambers

      The chamber consists of 2.3-m high, 3.3-m diameter cylinders with aluminum frames and covered by transparent polyethylene. The chambers, erected on a concrete platform, are used with potted plants. Air is blown into the chambers through a plenum around the inside of the wall at a rate of 1.15 m s^{-1}. The air entering filtered chambers passes through activated charcoal filters, while other chambers receive ambient air. The chambers are being rebuilt as semi-open-top chambers for studies on the effects of O_3 and acidic mist on trees. A curved roof, 3.45 m in diameter, is being placed over the chambers to exclude ambient rain. The edges are 0.15 m above the chamber rim and centers are 0.25 m above the top of the chamber.

   b. Pollutant Dispensing and Monitoring

      The chambers originally had only filtered or ambient air, with no extra pollutant dispensing. Ozone is monitored continuously with an ultraviolet analyzer. For O_3-acid mist studies, ozone is added, generated by a high voltage generator with concentrations controlled by altering voltage and flow rate to chambers. Acid mist is generated by 2 spinning disc humidifiers in each chamber. Droplet size is 5-20 u, with a mean of 11 u. Each humidifier emits 0.4 l hr^{-1}.

   c. Environmental Control and Monitoring

      The chamber environment is not controlled. Irradiance and air temperature in the chamber are measured.

   d. Data Acquisition

      Ozone concentration is recorded every 5 minutes in a datalogger.

2. Performance Evaluation

a. Pollutant Uniformity

Ozone exclusion at the top of the plant canopy in filtered chambers is approximately 20% of ambient, but changes with outside wind speeds.

b. Environment Uniformity

Irradiance in the chambers is > 90% of outside. Air temperature in the chambers is 3-4°C higher than outside on days with high light intensity. Plant injury response to ambient air in chambers is similar to the response to ambient air outside of the chambers. Air velocity over the plant canopy is 0.35-0.55 m sec^{-1} for the acid mist studies.

c. Pollutant Control and Maintenance

Not described.

d. Environmental Control and Maintenance

Not described.

e. Chamber Equilibration

There are 2.4 air exchanges per minute in the older chambers. This is increased to 4.7 air exchanges per minute in the new chamber design for the ozone-acid mist studies.

Publication: Jager, H.-J. 1986. Personal communication.

Location: Institut fur Produktions-und Okotoxikologie, Bundesforschungsanstalt fur Landswirtschaft, Braunschweig, Federal Republic of Germany

Summary: A semi-open-top field chamber facility was designed, constructed, and put into operation for determining the effects of ambient air pollutants and rain on plants. The chambers currently are being used for an experiment with winter barley.

1. Hardware

   a. Chambers

Eight cylindrical semi-open-top field chambers were constructed. The chambers are of the Heagle et al. (1973) design as modified by Hogsett et al. (1985). Each chamber is 3.5 m diameter, and 3.5 m high, including a 45° frustum at the top and rain cap. The frames are aluminum, and coverings are a low density polyethylene which has been UV light stabilized. Each chamber blower has a coarse particulate filter and fine particulate filter. Each filtered chamber has activated charcoal filters impregnated with 10% K_2CO_3. The blowers have a maximum air flow capacity of 43 m^3 min^{-1} at a counter pressure of 55 mm (550 Pa).

   b. Pollutant Dispensing and Monitoring

Sulfur dioxide is dispensed into some of the chambers from a tank of pure SO_2 via a mass flowmeter, mixing tank (for combination with clean air), pumps, and enters at the lower outlet to the chamber. The SO_2 is routinely monitored with a fluorescent analyzer. Ozone is monitored with a UV-absorption analyzer. Nitrogen oxides are measured with a chemiluminescent analyzer. A simulated rain solution is dispensed in the center of the chambers at 2.6 m above the ground.

   c. Environmental Monitoring and Controls

Ambient rainfall is controlled in the chambers. No information is given concerning other environmental factors.

   d. Data Acquisition

Not described.

2. Performance Evaluation

   a. Pollutant Uniformity

Not described.

b. Environment Uniformity

Irradiance is reduced 18-22% inside the chambers. Air temperature in the chambers varies with irradiance: 2.2°-2.8°C warmer during daylight with low-high irradiances. At night, chambers are less than 1°C different from ambient.

c. Pollutant Control and Maintenance

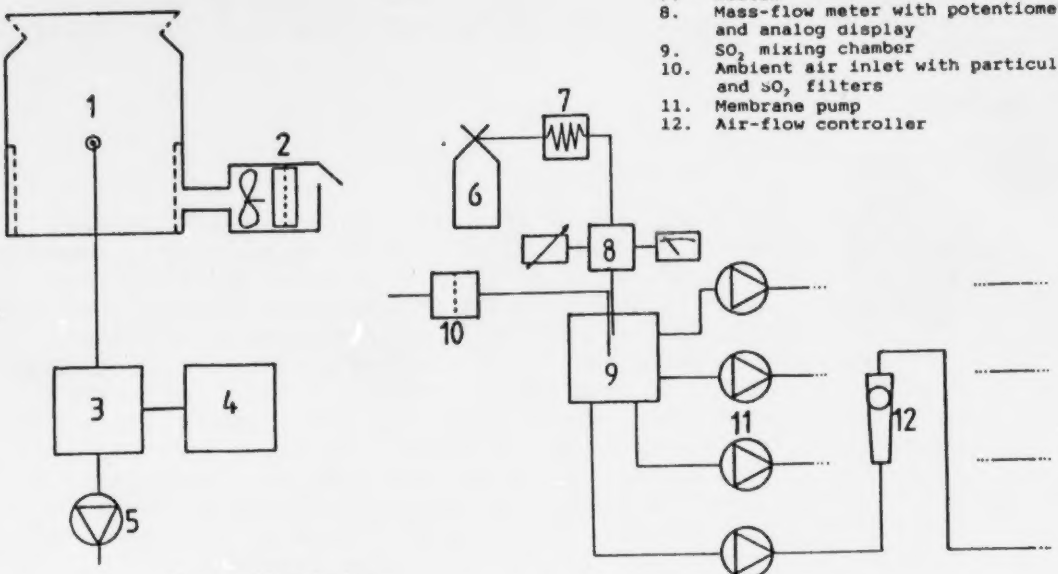
Efficiency of charcoal-filtration showed 58-64% removal of SO_2 for incoming ambient air. Data not given for NO_2 or O_3. NO is not removed.

d. Environment Control and Maintenance

Not described.

3. Chamber Equilibration

There are approximately 2.3 air exchanges per minute.



SO_2 Dosage System

6. SO_2 gas tank
7. Heater
8. Mass-flow meter with potentiometer and analog display
9. SO_2 mixing chamber
10. Ambient air inlet with particulate and SO_2 filters
11. Membrane pump
12. Air-flow controller

SO_2 Monitor System

1. Open-top chamber
2. Fan with filter system
3. SO_2 monitor
4. Printer
5. Pump

Figure D-1. Schematic diagram of semi-open-top field chamber and pollutant dispensing system at Braunsweig (Jager, H.-J., 1986, personal communication).

Publication: Krause, G. 1986. Personal communication, and Pfeffer, H.-U. 1982. Das Telemetrische Echtzeit-Mehrkomponenten-Erfassungs-System TEMES zur Immissionsuberwachung in Nordrhein-Westfalen, LIS-Berichte, 19, Landesanstalt fur Immissionsschutz des Landes Nordrhein-Westfalen, Essen, Federal Republic of Germany.

Location: Landestalt fur Immissionsschutz des Landes Nordrhein-Westfalen, Essen, Federal Republic of Germany

Summary: A new semi-open-top field chamber facility has been designed, constructed, and put into operation for determining the effects of ambient pollutants on trees. The chambers have either filtered or ambient air treatments, and treatments of ambient rain collected on a large nearby surface.

1. Hardware

a. Chambers

The facility consists of eight semi-open-top field chambers based on the design of Heagle *et al.* (1973), as modified by Hogsett *et al.* (1985). Each chamber is 3.0 m in diameter and 2.4 m high. Above each chamber is an 8.5 m high frustum which inclines inward by 45°; and 0.3 m above the frustrum is a 2.7-m diameter, 0.6-m high rain cap. The chambers have rigid aluminum frames, and are covered with PVC film which is temperature resistant between -25 to +50°C, and UV light resistant. Air is blown into the chambers from a radial blower at a variable rate ranging from 8.3 to 117 m^3 min^{-1} at pressures of 0 to 870 Pa. A typical operating air flow rate is 58 m^3 min^{-1}. Air enters the chambers through a donut-shaped plenum around the base of the chambers. The trees are placed in 1.0-m deep, 0.8-m diameter lysimeters, with six lysimeters per chamber.

Ambient wet deposition is collected on a 30 m^2 roof of fibrous polyester material adjacent to the chambers. The surface of the roof is the same as the area within the four ambient rain chambers. The rain is collected for 24-hour periods for particular events, and deposited in chambers at 0300 the next day. The blowers are turned off during rain events. Four other chambers receive simulated rain at the same time as the collected ambient rain treatment. The simulated rain is based on annual means for rain data collected in the Italian Alps. All rain treatments are delivered through stainless steel nozzles with a mean droplet size of 0.5 mm at a rate of 0.17 mm m^{-2} min^{-1}. The blowers are turned on again at 0600 following the rain treatments.

b. Pollutant Dispensing and Monitoring

No gaseous air pollutants are dispensed into the chambers. Routine monitoring of SO_2, NO_x, CO, O_3, coarse, and fine particulates is via the automated TEMES measuring system (Pfeffer, 1982).

c. Environmental Monitoring and Controls

Simulated rain is dispensed in the chambers as described above. Routine monitoring of environmental parameters (air temperature, relative humidity, precipitation, solar radiation, wind speed, and wind direction) is via the TEMES system.

d. Data Acquisition

Mainframe computer.

2. Performance Evaluation

a. Pollutant Uniformity

Not described.

b. Environment Uniformity

Air flow over the plant canopy is approximately 0.02 to 0.24 m s^{-1}. Air temperature in the chambers is 1.5°C warmer than outside with solar radiation and 35°C. Air temperature in chambers is 0.5°C warmer than outside without solar radiation and an air temperature of 25°C. Irradiance is reduced by approximately 18% in the chambers compared to outside, but light quality is the same in chambers and outside. Relative humidity is lower in chambers than outside by the same proportion as air temperature is increased.

c. Pollutant Control and Maintenance

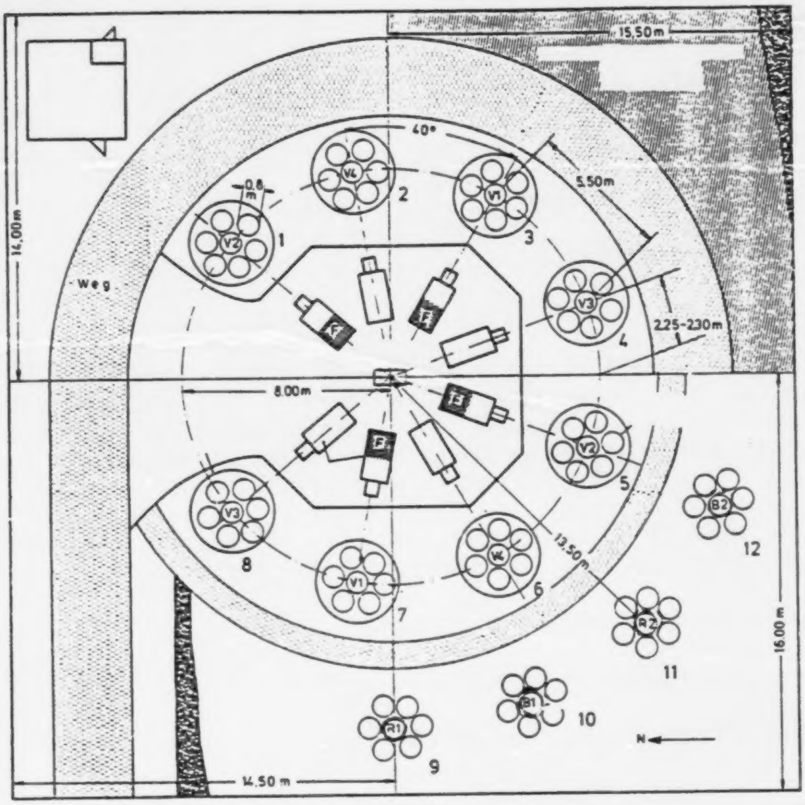
Not described.

d. Environment Control and Maintenance

Not described.

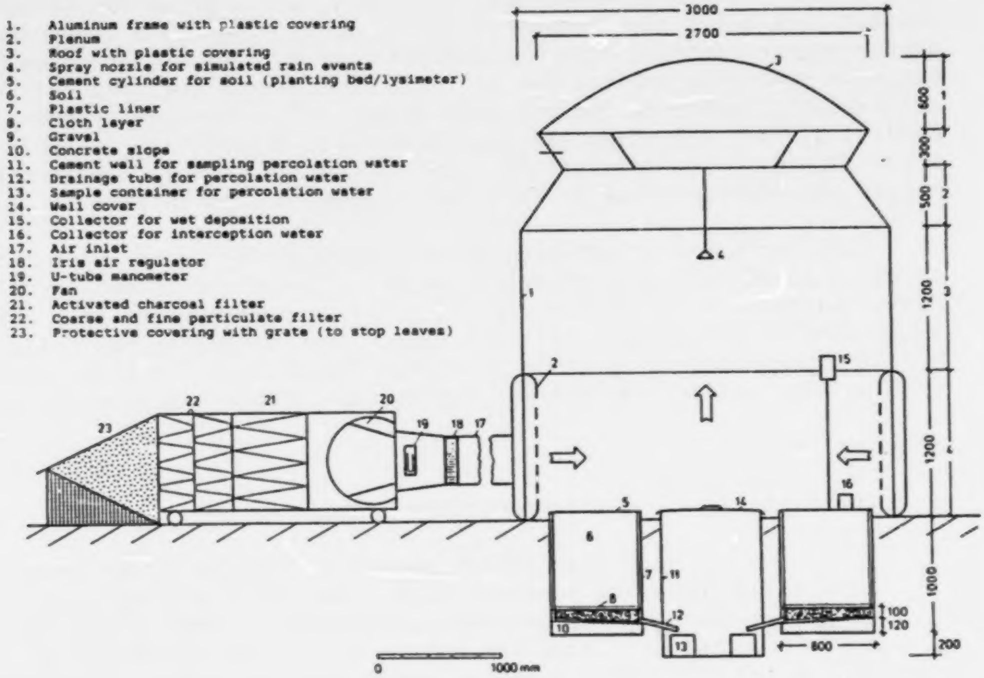
3. Chamber Equilibration

There are 0.4 to 4.6 air exchanges per minute, with a typical rate of 2.3 per minute.



V1	filtered air/ambient rain
V2	filtered air/simulated rain
V3	ambient air/ambient rain
V4	ambient air/simulated rain
R1-B1	reference without chambers

Figure D-2. Schematic diagram of semi-open-top field chamber facility of L.I.S. (Krause, G., 1986, personal communication).



1. Aluminum frame with plastic covering
2. Plenum
3. Roof with plastic covering
4. Spray nozzle for simulated rain events
5. Cement cylinder for soil (planting bed/lysimeter)
6. Soil
7. Plastic liner
8. Cloth layer
9. Gravel
10. Concrete slope
11. Cement well for sampling percolation water
12. Drainage tube for percolation water
13. Sample container for percolation water
14. Well cover
15. Collector for wet deposition
16. Collector for interception water
17. Air inlet
18. Iris air regulator
19. U-tube manometer
20. Fan
21. Activated charcoal filter
22. Coarse and fine particulate filter
23. Protective covering with grate (to stop leaves)

Figure D-3. Schematic diagram of semi-open-top field chamber, air handling system, and soil solution sampling system of L.I.S. (Krause, G., 1986, personal communication).

Publication: Kuja A., R. Jones, and E. Enyedi. 1986. A mobile rain exclusion canopy and gaseous pollutant reduction system to determine dose-response relationships between simulated acid precipitation and yield of field grown crops. Water, Air, Soil Pollut. 31:307-315.

Location: Ontario Ministry of the Environment, Brampton, Ontario

Summary: A system has been designed, constructed, and tested to determine the interaction between acidic rain and ambient oxidants on agricultural crops. The system uses a duct air-exclusion system for reducing ambient gaseous air pollutant levels (O_3, SO_2, NO_x), and a cover to exclude ambient rain while simultaneously adding acidic rain to a crop canopy. A microcomputer controls both the inflation of the air-exclusion system based on specified ambient air pollution concentrations, and rain exclusion/addition based on ambient rain events. The computer system also handles all air pollution and rain event data acquisition, as well as meteorological data acquisition. The system has been tested in studies of radish and soybean crops in 1984, and a soybean crop in 1985.

Rain exclusion is achieved by an automated exclusion shelter activated by an ambient precipitation sensor. During exclusion in sheltered plots, rainfall is dispensed automatically through nozzles at a rate equivalent to the natural rainfall rate. The shelter is basically a modified greenhouse wrapped in plastic. The size of the plots sheltered from ambient rainfall allows for replication within a single shelter unit.

1. Hardware

   a. Ducts and Rain Exclusion/Addition System

      The air exclusion system consists of three blower units, each containing three low pressure fans. Two units are equipped with activated-charcoal filters and particulate filters to supply filtered air; the other unit supplies ambient air. The air is forced into two 15.2-m long by 0.30-m diameter perforated PVC ducts. Each system has a mobile greenhouse shelter (19.5 x 9.1 x 4.6 m) constructed of galvanized steel covered with PVC. The shelter rolls on wheels on steel tracks over the duct systems during each ambient rain event. Whirl-jet type, stainless steel nozzles deliver 1-mm diameter simulated rain to the plots during the rain events. The entire system is replicated three times. The surface area for planting is 174 m^2, with a maximum height of 2.4 m.

   b. Pollutant Dispensing and Monitoring

      The gaseous pollutant treatments are ambient or charcoal-filtered air; no other gases are added. Ambient air concentrations of O_3, SO_2, and NO/NO_2 are measured by monitors in a control trailer.

      The simulated acidic rain included five pH treatments of 3.0, 3.4, 3.8, 4.2, and 5.6; each with mineral salts and a 2:1 SO_4/NO_3 ratio based on ambient rainfall chemistry. The simulated rain solutions were mixed immediately before each event by a computerized system. The activation of the exclusion shelter is achieved by a rain sensor monitored by a minicomputer. The rate of ambient rainfall is monitored with a tipping-bucket rain gauge. Minimum rainfall needed to trigger dispensing of the rain simulant is 0.5 mm. Rain is dispensed from stainless steel nozzles that deliver droplets in a square pattern. Rain simulant is delivered by pumps from reservoirs, and the flow rate through the lines is controlled by PVC needle valves and pressure gauges. All mixing of solutions is achieved in the batch mode but is done automatically by a system of light switches, pumps, and solenoid valves.

The method for chemically analyzing the simulated rainfall is not specified. The reported chemistry is for batch or in-line solutions and is calculated based upon recipe additions. The method for measuring the rainfall distribution/application rate within the shelter, either on a routine basis or as a means of evaluating performance, is not reported.

c. Environmental Monitoring and Controls

Air temperature, relative humidity, wind velocity, and light intensity are monitored continuously and the data stored by the data acquisition system.

d. Data Acquisition

All aspects of the field system are controlled by a microcomputer and data acquisition system. The data commonly logged include status of mixing and treatment pumps, blower activation, storage tank levels, air temperature, relative humidity, wind velocity, irradiance, and ambient levels of gaseous pollutants. For the meteorological data, a 30-min averaging time is used.

2. Performance Evaluation

a. Pollutant Uniformity

Gaseous pollutant distributions not described. Rain chemistry is calculated from the solution mixture. Soil deposition rates are calculated rather than measured with rain events.

b. Environment Uniformity

Not described.

c. Pollutant Control and Maintenance

Not described.

d. Environment Control and Maintenance

Not described.

Diagram of the system was not available.

Publication: Seufert, Von G., and U. Arndt. 1985. Open-top kammern als teil einer konzepts aur okosystemaren unter suchung der neuartigen woldschaden. Allg. Forstz. 40:13-20.

Additional Publication: Arndt, U. 1986. Proceedings of Open-Top Chamber Workshop, Environmental management in open-top chambers. Freiburg, Federal Republic of Germany. Commission of the European Communities.

Location: Institut fur Landeskuetur und Pflanzenokologie, University of Hohenkiran, Stuttgart, West Germany

Summary: A system of six open-top chambers are part of model ecosystems with lysimeters and protection from ambient rain to investigate long term effects of SO_2, O_3, and acid rain on mineral cycling, biochemistry, ecophysiology, and anatomy of tree seedlings.

1. Hardware

   a. Chambers

      The chambers are 3-m diameter cylinders, 3 m in height, with a frustrum and an inside area of 3.2 m^2. UV-B stabilized PVC film (Polydress SPR 3) cover the chambers. Each chamber has a blower fan (56 m^3 min^{-1}) and filtration system of activated charcoal with KOH and dust filters. The trees are planted in ground-level lysimeters.

   b. Pollutant Dispensing and Monitoring

      Only ambient gaseous pollutants and filtered chambers are in use; no added pollutant except acid rain. The incoming air is distributed from the center with three perforated PVC tubes extending out along a footpath. Each chamber is monitored for SO_2, $O_3{}^2$, and NO_2, but frequency of sampling is not reported.

   c. Environmental Monitoring and Controls

      Chamber environment is not controlled except "rain cap" excludes ambient precipitation. Relative humidity, evapotranspiration, soil moisture, and soil temperature (at 10 and 30 cm) are routinely measured in all chambers. The frequency of measurement of air temperature and solar radiation is not described.

   d. Data Acquisition

      Not described.

2. Performance Evaluation

a. Pollutant Uniformity

The chambers exclude between 60 and 95% of the ambient O_3, the average is 80%. No information on exclusion of other pollutants is described. Ambient rainfall is excluded, but no information on amounts is provided. There was no information on pollutant variability across the chamber or over time.

b. Environment Uniformity

The chambers have an irradiance 30% lower than outside without the shadecloth, and 45% lower than outside with the shadecloth. This low irradiance is considered to be more representative of forest environments than full sunlight. Chamber air temperature is 0 to 5°C greater, and relative humidity is 0 to 15% greater than outside if no chamber modifications are made. The chamber has been adapted to include fog nozzles which raise the relative humidity to within 5% of the outside; this is accompanied by a decrease in chamber temperature. Air speed within the chamber is estimated at 0.5 to 1.0 m sec^{-1}, which is adequate for high boundary layer conductances. No information was described concerning the location or frequency of environmental measurements, or uniformity vertically, horizontally, or temporally across or between chambers.

c. Pollutant Control and Maintenance

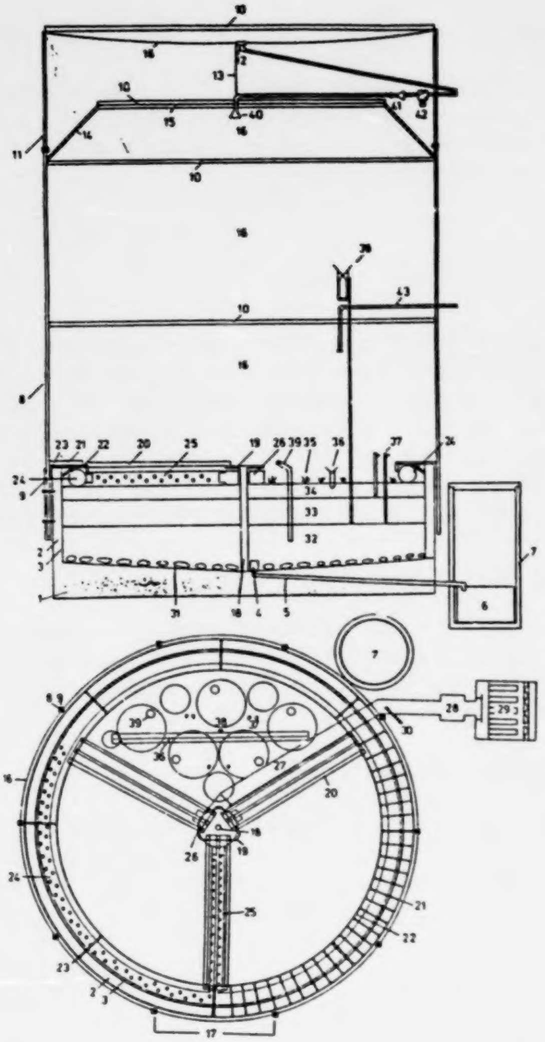
Ambient and charcoal-filtered air is put into the chambers. Filtration efficiency is not described for O_3, SO_2, NO_2, and NO. Intrusion of pollutants in the open top is a function of wind speeds and varies between 70% with strong winds and not detectable with wind speeds less than 0.5 m sec^{-1}. Mean chamber efficiency given as 80% exclusion of O_3 and SO_2.

d. Environment Control and Maintenance

Not described.

e. Chamber Equilibration

There are approximately 1.5 air exchanges per minute.



1. basement of concrete
2. lysimeter-walls, concrete 80x8 cm, Ø 3 m
3. sealing up of concrete with PE-foil 2 mm
4. drain for percolating water
5. PE-tube 3/4"
6. PE-container 60 l
7. drainage-shaft, h = 110 cm, d = 60 cm
8. frame of coated iron-tubes 1/2"
9. mounting for the frame
10. coated strip iron 30x3 mm
11. holding device for rain-shelter
12. rain outlet
13. line to strain the rain-shelter-foil
14. frustrum 45°, 50 cm
15. Al-profile for stabilization
16. PVC-foil 0,2 mm, UV-stabilized
17. foil-door
18. 19. central support for footbridge
20. 21. footbridge
22. 23. peripheral support for footbridge
24. annular ventilation tube, d = 125 mm
25. ventilation tube between center and annulus
26. central air-distribution
27. air-duct from blower
28. blower 2200 W, 56 m³/min
29. filter element with carbon-cartridges and particle-filter
30. dispensing teflon-line for gases
31. draining stowe-material
32-34. soil-horizons
35. ground-flora
36. sampling-duct for crown leachate
37. keramic candles for soil solution
38. bulk sampler
39. rhizoskope-tube
40. rain nozzle
41. 42. magnetic valve, pressure control valve, water clock
43. sample-line to analysers

Reproduced from best available copy.

Figure D-4. Schematic diagram of open-top chambers at University of Hokenheim, Stuttgart, West Germany (U. Arndt, personal communication, 1986).

Publication: Seufert, Von G., and U. Arndt. 1985. Open-top kammenn als teil einer konzepts aur okosystemaren unter suchung der neuartigen woldschaden. Allg. Forstz. 40:13-20.

Location: Edelmannshof station in Welzheimer Wold at Aufbau, Germany

Summary: Four large open-top chambers built around four healthy mature spruce trees in a diseased forest area. The chambers are designed to investigate the long-term effects of ambient and filtered air on mineral cycling, biochemistry, ecophysiology, and anatomy.

1. Hardware

   a. Chambers

      Each chamber is a 6 x 2.5 m cylinder with a ground area of 4.9 m^2 and volume of 2.9 m^3. Air is drawn into the chambers with two blowers delivering air to the plenum at the lower and upper levels of the chamber. Blowers run full speed for the upper level at all times (18-20 m^3 min^{-1}); the lower level (0-20 m^3 min^{-1}) depends on ambient wind speed and is off at night to allow dew formation. Charcoal filters impregnated with KOH are in use on each blower fan.

   b. Pollutant Dispensing and Monitoring

      No dispensing occurs in the chambers, only filtered and ambient air. Monitoring of O_3 is by analyzer and monitoring of SO_2 and NO_2 is by surface active monitoring at 10 places within each chamber. The frequency of sampling is not described.

   c. Environmental Monitoring and Controls

      Chamber environment is not controlled. Relative humidity, evapotranspiration, soil moisture, and soil temperature (10- and 30-cm depth) are routinely measured in all chambers. Measurement of air temperature and irradiance are not described.

   d. Data Acquisition

      Not described.

2. Performance Evaluation

   a. Pollutant Uniformity

      Distribution within each chamber is not described. Chamber efficiency in excluding ambient pollutant is improved by plastic netting at the outlet. Initial measurements show incursion starting at wind speeds of more than 1 m sec^{-1}.

b. Environment Uniformity

Variation within each chamber is not described. Inside versus outside temperature and solar radiation show 2-3°C increases in temperature and 10-25% reduction in photosynthetic active radiation (PAR) inside the chambers. Wind speed at the twigs varies between 0-2 m sec^{-1}.

c. Pollutant Control and Maintenance

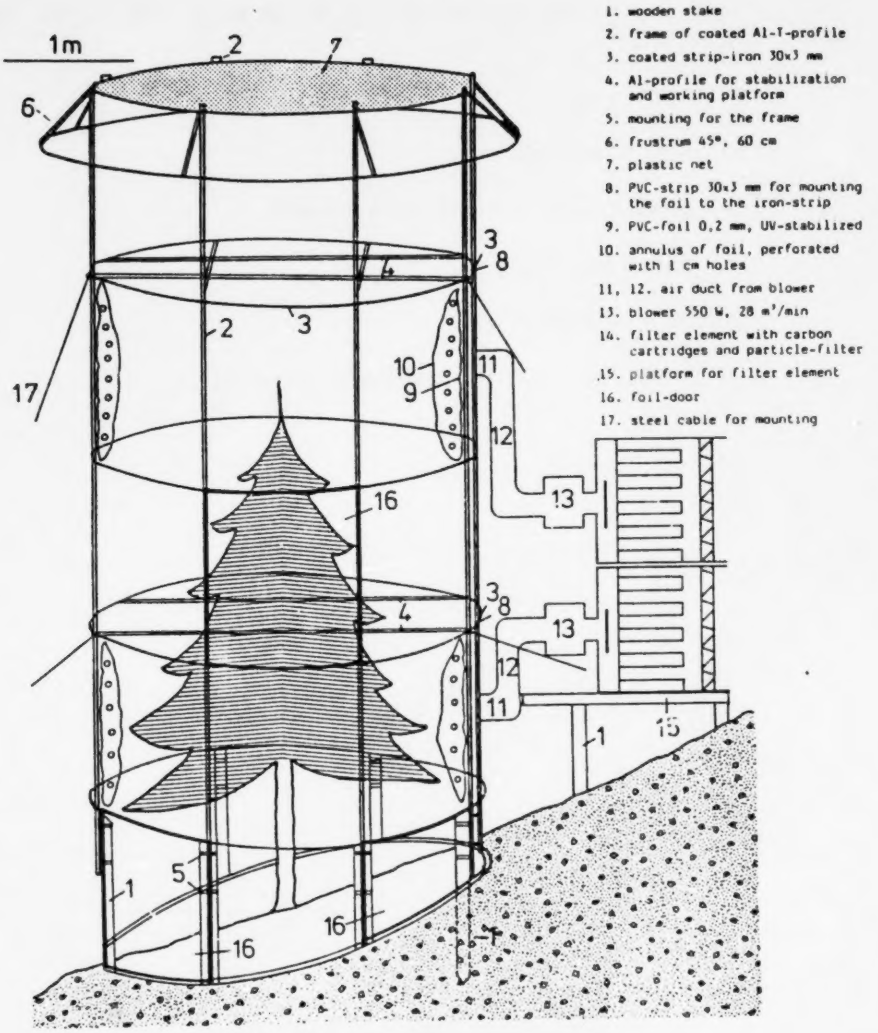
Not described.

d. Environment Control and Maintenance

Not described.

e. Chamber Equilibration

There are 1-2 air changes per minute.


1m
2
7
6
3
8
4
2
3
17
10
11
9
12
13
16
13
3
8
4
12
11
15
1
5
1
16
16
1
1. wooden stake
2. frame of coated Al-T-profile
3. coated strip-iron 30x3 mm
4. Al-profile for stabilization and working platform
5. mounting for the frame
6. frustrum 45°, 60 cm
7. plastic net
8. PVC-strip 30x3 mm for mounting the foil to the iron-strip
9. PVC-foil 0,2 mm, UV-stabilized
10. annulus of foil, perforated with 1 cm holes
11, 12. air duct from blower
13. blower 550 W, 28 m³/min
14. filter element with carbon cartridges and particle-filter
15. platform for filter element
16. foil-door
17. steel cable for mounting

Reproduced from best available copy.

Figure D-5. Design of open-top chambers at Edelmanshof for ambient air pollutant exclusion (U. Arndt, personal communication, 1986).

APPENDIX E

Descriptions of Facilities and Performance Evaluations -- Indoor Chambers for Gaseous Dry Deposition Research

I. Chambers for Laboratory Use

Publication: Adams, D. F. 1961. An air pollution phytotron. A controlled environment facility for studies into the effects of air pollutants on vegetation. J. Air Pollut. Contr. Assoc. 11:470-476.

Location: Washington State University, Pullman, Washington

Summary: This paper reports the design of a controlled exposure facility (phytotron) in which light, temperature, humidity, air circulation, and pollutant concentrations may be controlled for the studying of plant responses to atmospheric pollutants.

1. Hardware

The facility uses plant growth chambers, an air handling system, a lighting system, and a pollutant (fluoride) generating system.

a. Chambers

A controlled environment room is divided into three walk-in chambers, one large and two small. The large chamber is used to germinate and grow plants to any selected state of maturity. The plant population is divided into the two smaller chambers for paired experiments of unexposed (control) and exposed plants. Incoming filtered and conditioned air is introduced through a perforated ceiling, creating a nearly uniform air flow into the chambers. The exhaust ducts at floor level have numerous openings to help maintain an even air flow. The light source is a combination of fluorescent and incandescent lamps.

b. Pollutant Dispensing and Monitoring

Hydrofluoric acid vapor is generated and introduced into the incoming chamber air stream.

c. Environment Controls

Not described.

d. Data Acquisition

Not described.

2. Performance Evaluation

a. Pollutant Uniformity

Ten bench locations had an average variation of ± 5.9% from the mean.

b. Environment Uniformity

Light levels varied horizontally by about 30% in the large chamber and 20% in the small chambers.

c. Pollutant Control and Maintenance

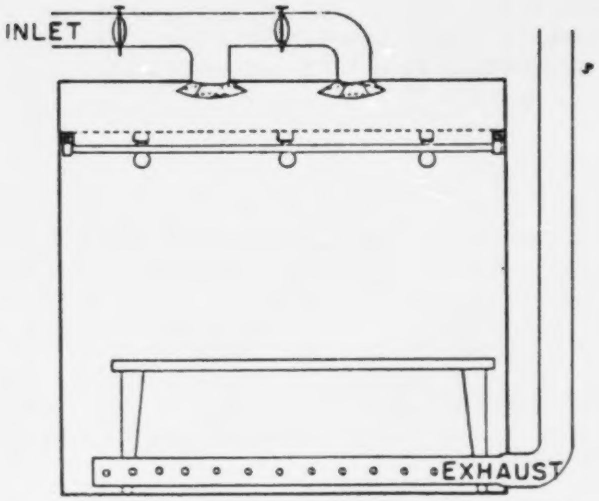
Diurnal variations of the chamber fluoride concentration were found and were associated with variations in incoming air temperature. There is more adsorption of fluorides on cooler chamber walls at night than on warmer walls during the daytime.

d. Environment Control and Maintenance

Not described.

e. Chamber Equilibration

Not described.



PHYTOTRON CROSS - SECTION

Figure E-1: Controlled environment chamber for fluoride research (reprinted from Adams, 1961, with permission of the Air Pollution Control Association).

Publication: Aiga, I., K. Omasa, and S. Matsumoto. 1984. Phytotrons in the National Institute for Environmental Studies. Res. Rep. Natl. Inst. Environ. Stud., Japan 66:133-154.

Location: National Institute for Environmental Studies, Ibaraki, Japan

Summary: This paper describes two phytotrons, one with controlled greenhouses and growth cabinets; the other with simulators to analyze the plant-environment system. In the controlled greenhouses, there are four growth cabinets for studying the effect of air pollutants on plants under natural light and nine growth cabinets (described below) for studying air pollutants under artificial light. The phytotron with two simulators (growth rooms) reproduces a plant community's light, air, and soil, to examine the effect of environmental deterioration on plants.

1. Hardware

   a. Chambers

      Each controlled exposure chamber consists of a fresh air processing unit, a chamber for gas exposure experiments, and an exhaust processing unit. The fresh air for ventilation is introduced through an air conditioner and filters of both activated carbon and manganese. Each simulator is a special wind tunnel of the low wind velocity type. It includes an air conditioner and profile units for wind velocity, air temperature and humidity. There is a solar simulator to control light spectrum and intensity and a soil environment control unit.

   b. Pollutant Dispensing and Monitoring

      The gas, supplied from a cylinder or an ozone generator, is manipulated by a mass flow controller. A gas analyzer is used for a feedback sensor. These can be programmed to control gas concentration for both single and mixed gases.

   c. Environment Controls

      Temperature from 15 to 40°C and relative humidity from 50-80% are controlled by a central cold water and steam system. For lighting, metal halide lamps with the emission spectrum of tin halide are used. Phosphide glass containing iron oxide is used as a heat-absorbing filter. Mean wind velocity is 0.2 m sec^{-1} with 0-2800 m^3 h^{-1} ventilation. In the simulator the profile unit for air temperature and humidity is composed of 10 stages, each of which can be independently regulated by computer control to provide any spatial distribution of temperature up to 10°C and humidity up to 50%. The wind velocity profile up to 8X minimum is produced by retardation using a 10-stage profile unit after preconditioning by the main blower. The light spectrum and intensity of 4 to 60 Klux are regulated by various fluorescent lamps with different spectral characteristics. Both soil temperature (-5 to +35°C) and water content can be regulated. The range of wind velocity is 0.1 to 2.7 m s^{-1} with ventilation of 50-250 m^3 h^{-1}.

d. Data Acquisition

Not described.

2. Performance Evaluation

a. Pollutant Uniformity

For the controlled exposure chamber the deviations of gas concentration are: SO_2 ± 3.2 ppb (at 0.05 ppm), NO_2 ± 0.6 ppb (at 0.05 ppm), O_3 ± 0.2 ppb (at 0.01 ppm) and HC ± 10 ppb (at 0.2 ppm). For the simulator the corresponding values are: SO_2 ± 3.2 ppb (at 0.05 ppm), NO_2 ± 0.6 ppb (at 0.5 ppm), O_3 ± 0.2 ppb (at 0.01 ppm) and HC ± 10 ppb (at 0.2 ppm).

b. Environment Uniformity

For the controlled exposure the maximum temperature deviation is ± 0.1°C and maximum distribution ± 0.3°C, humidity deviation ± 1% RH and distribution ± 2% RH, wind distribution ± 0.1 m s^{-1}. For the simulator the corresponding values are temperature ± 0.1°C and ± 0.3°C, humidity ± 0.1°C (dew point) and ± 0.2°C (dew point), and wind ± 0.1% and ± 3% with turbulence intensity of ± 3%. The deviation in lighting is ± 0.1% and distribution ± 10 lux at 50 Klux. Brine temperature deviation is ± 0.1°C for the soil temperature control system.

c. Pollutant Control and Maintenance

Included above under uniformity.

d. Environment Control and Maintenance

Included above under uniformity.

e. Chamber Equilibration

Not described.

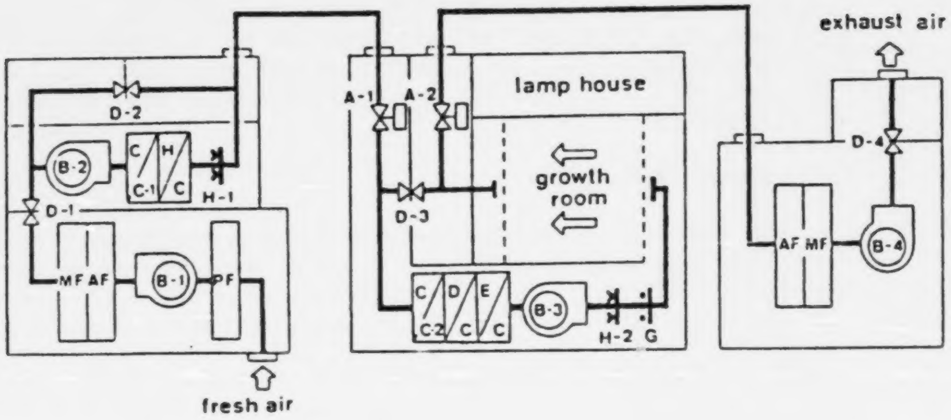


Figure E-2. Sectional view of the growth cabinet for air pollutant exposure (reprinted from Aiga et al., 1984, National Institute of Environmental Studies).

Publication: Cantwell, A. M. 1968. Effect of temperature on response of plants to ozone as conducted in a specially designed plant fumigation chamber. Plant Dis. Reptr. 52:957-960.

Location: Department of Plant Pathology, University of Delaware, Newark, Delaware

Summary: A commercial plant growth chamber was modified for air pollution studies in which temperature was to be a treatment factor.

1. Hardware

   a. Chambers

      Filtered air is provided to the chamber through an inlet blower and filter system. About 90% of the air is recirculated and 10% is ambient. The growth chamber contains an enclosed glass fumigation chamber. Lighting is by the combination of fluorescent and incandescent lights in the chamber.

   b. Pollutant Dispensing and Monitoring

      Conditioned air in the growth chamber is mixed with a gaseous pollutant and passed through a turbulence-inducing distribution tube. The air pollutant then enters the fumigation chamber where it contacts the plant, and subsequently is vented to the atmosphere. Pollutant concentration within the fumigation chamber is continously monitored by withdrawing samples through tubing to the appropriate monitor.

   c. Environment Controls

      Temperature and humidity are controlled by the growth chamber system.

   d. Data Acquisition

      Not described.

2. Performance Evaluation

   a. Pollutant Uniformity

      Not described.

   b. Environment Uniformity

      Not described.

c. Pollutant Control and Maintenance

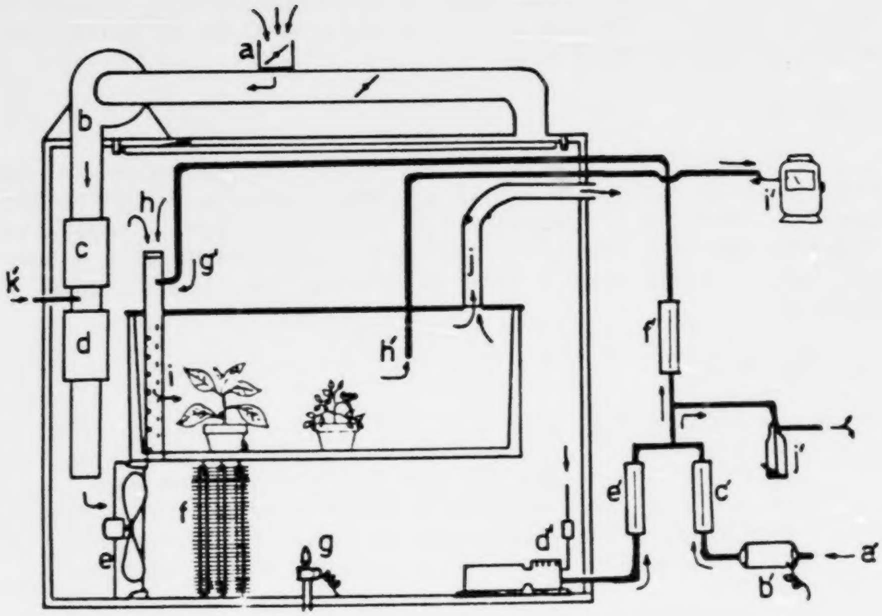
Ozone levels of 0.1 to 100 pphm can be maintained in the fumigation chamber with a maximum variation of ± 5%.

d. Environment Control and Maintenance

Not described.

e. Chamber Equilibration

About 2 hours are required before the unit operates at equilibrium and the pollutant saturates the absorbing surfaces in the tubing and chamber. Following this initial period, substantial changes in pollutant concentrations can be stabilized within 10 to 15 minutes.



a - air inlet to conditioning chamber
b - high pressure blower
c and d - activated charcoal filters
e - circulating fan
f - refrigeration unit
g - humidifying unit
h - inlet to fumigation chamber
i - distribution tube
j - air outlet tube

a' - oxygen inlet
b' - ozone generator
c' - ozone flow controller
d' - pure air pump
e' - pure air flow controller
f' - air pollutant flow controller
g' - air pollutant inlet line
h' - pollutant sampling line
i' - pollutant analyzer
j' - pollutant scrubber
k' - oxidant injection line

Figure E-3. Controlled environment chamber for ozone research (reprinted from Cantwell, 1968, Plant Disease Reporter).

Publication: Hill, A. C. 1967. A special purpose plant environmental chamber for air pollution studies. J. Air Pollut. Contr. Assoc. 17:743-748.

Location: Department of Botany, University of Utah, Salt Lake City, Utah

Summary: These controlled exposure chambers utilize an airtight, recirculating air system with controlled addition of CO_2. Air velocity can be controlled. Temperature and humidity are maintained by a water temperature control system. The air pollutant concentration is maintained by automatic or manual additions.

1. Hardware

The facility consists of an airtight controlled-environment chamber with internal recirculation of air and provision for different wind speeds. There is a carbon dioxide control system. Temperature and relative humidity are controlled over a wide range with a combination of cooling and heating coil temperatures and the circulating of air through a water bath.

a. Chambers

Each chamber consists of a light bank, plant area, stands, and conditioning unit bolted together, with joints sealed, and foam insulation in the walls. Air is circulated through a perforated wall across the plant area with a variable proportion circulated through water coils. The light bank consists of fluorescent, quartz iodide, and incandescent lamps, with infrared absorbing filters.

b. Pollutant Dispensing and Monitoring

In this chamber the pollutant concentration is controlled, once the desired level is reached, by adding the pollutant to the chamber at the same rate that it is being lost by the system. A glass sampling tube on the exterior of the chamber connecting the two plenums of the chamber has continuous air flow because of a pressure differential. Ozone is injected into the chamber at the fan inlet to facilitate thorough mixing with chamber air.

c. Environment Controls

Air flow rates can be modified by blocking off part of the inlet and outlet walls. Carbon dioxide concentration in the chamber is maintained by monitoring with an infrared analyzer controlling a valve that admits CO_2 from a pressurized cylinder. Temperature is controlled by water temperature in cooling coils. Humidity is controlled over a wide range by a combination of circulating air through cold and warm water coils for low humidities and by circulating air through a warm water bath to obtain high humidities. Operator experience is an important factor in control of environmental variables that are affected by percentage of air flowing through the water coils, water flow rate through the coils, water temperature, and the number of cold coils in operation.

d. Data Acquisition

Not described.

2. Performance Evaluation

a. Pollutant Uniformity

Not described.

b. Environment Uniformity

The author reported that relative humidity in the range from 20 to 96% at 27°C can be maintained within ± 1%. Other variables not described.

c. Pollutant Control and Maintenance

Not described.

d. Environment Control and Maintenance

Not described.

e. Chamber Equilibration

Not described.

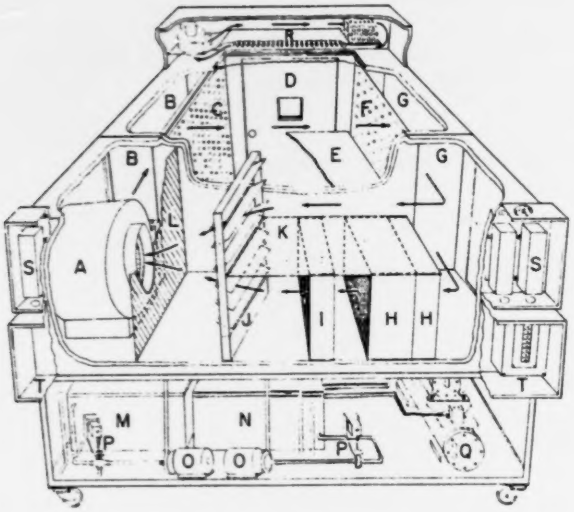


Figure E-4. Air circulation and conditioning components of the controlled environment chamber for air pollution research (reprinted from Hill, 1967, with permission of the Air Pollution Control Association).

Publication: Jensen, K. F., and F. W. Bender. 1977. Seedling-size fumigation chambers. Forest Service Research Paper NE-383. 4 p.

Location: Northeastern Forest Experiment Station, Research Laboratory, Delaware, Ohio

Summary: The design of fumigation chambers for forest tree seedlings is described. Each chamber has individual temperature, humidity, light, and pollutant control. Temperature is variable from 15 to 35°C and controlled within ± 1°C. Humidity is variable from 25 to 95% and controlled within ± 3%. Seedlings have been successfully grown in these chambers for up to 3 months.

1. Hardware

The fumigation system consists of four chambers with airflow, air conditioning, lighting, temperature control, humidity control, and pollutant addition components.

a. Chambers

The chambers are constructed of plywood painted with white epoxy. The airflow is negative-pressure, single-pass by means of a blower on each chamber. Air conditioning is by three separate compressor and evaporator coil units.

b. Pollutant Dispensing and Monitoring

Two pollutants can be added, individually or in combination, to each chamber. Additions are by micrometering valves to the air stream about 150 cm before the pollutant enters the chamber to allow ample mixing. Monitoring is by drawing a sample from the chamber.

c. Environment Controls

Lighting is by a bank of fluorescent and incandescent bulbs that can be turned out selectively to provide six different light levels. Temperature is monitored and controlled with shielded thermocouples. Each chamber has a 24-hour programmable controller.

d. Data Acquisition

Monitors alternate automatically between chambers and are connected to strip chart recorders. Temperature is also recorded.

2. Performance Evaluation

a. Pollutant Uniformity

Not described.

b. Environment Uniformity

Light level decreases approximately 20 percent from the center to the corners of each cabinet. Temperatures in the center and in each corner 15 and 45 cm above the floor are within a range of ± 1°C. Relative humidity has a variation of ± 3% at 23°C.

c. Pollutant Control and Maintenance

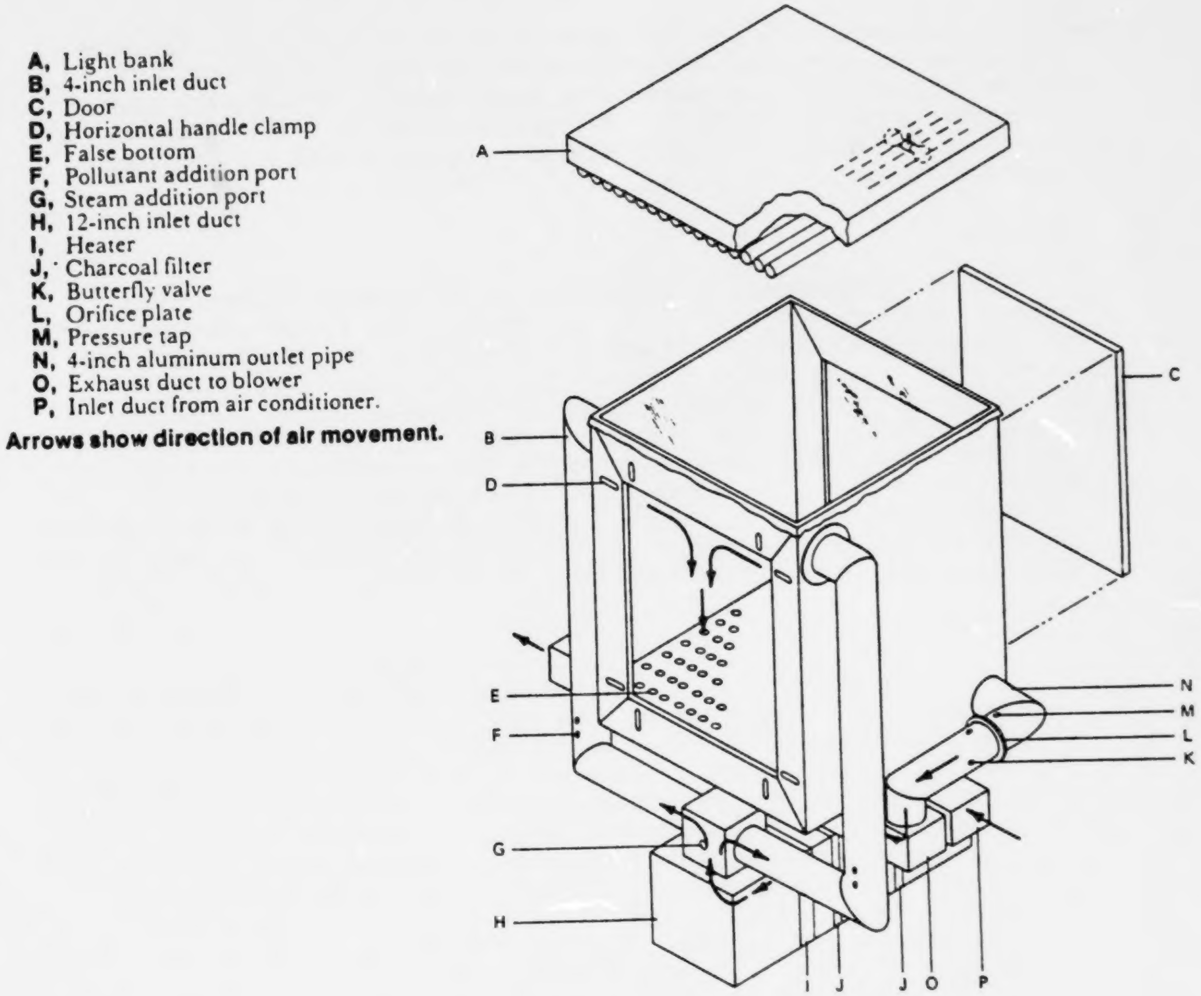
Pollutants can be added in a wide range of concentrations and maintained with slight adjustments for long periods.

d. Environment Control and Maintenance

Light levels at 30 cm above the floor can be set for about 10 to 30 Klux, temperatures from 15 to 35°C, and humidity 25 to 95% with the lower limit being higher at low temperatures.

e. Chamber Equilibration

Not described.



A, Light bank
B, 4-inch inlet duct
C, Door
D, Horizontal handle clamp
E, False bottom
F, Pollutant addition port
G, Steam addition port
H, 12-inch inlet duct
I, Heater
J, Charcoal filter
K, Butterfly valve
L, Orifice plate
M, Pressure tap
N, 4-inch aluminum outlet pipe
O, Exhaust duct to blower
P, Inlet duct from air conditioner.

Arrows show direction of air movement.

Figure E-5. View of controlled environment seedling chamber for air pollution research (reprinted from Jensen and Bender, 1977, U.S. Forest Service).

Publication: McLaughlin, S. B., V. J. Schorn, and H. C. Jones. 1976. A programmable exposure system for kinetic dose-response studies with air pollutants. J. Air Pollut. Contr. Assoc. 26:132-135.

Location: Tennessee Valley Authority, Muscle Shoals, Alabama

Summary: A programmable system for exposing plants to sulfur dioxide under controlled and reproducible concentration regimes is described. The system is capable of reproducing the rapid changes in pollutant concentrations that occur in the field. The system relies on feedback control to reproduce previously programmed exposure regimes within a controlled exposure chamber.

1. Hardware

The main components of the system are an exposure chamber, programmer, analyzer and controller, and valves. The system operates on the principle of feedback control whereby at any time the level of the programmed SO_2 concentration is compared with the actual concentration occurring within the exposure chamber to determine the volume of SO_2 injected into the chamber. Input and output signals are processed by a controller that continously compares the two signals as a basis for activating two low flow valves. The valves meter SO_2 into the air supplied to the exposure chamber. Sample air continously drawn from this chamber is analyzed to produce the output signal which is fed back to the controller and concurrently recorded.

a. Chambers

The chamber frame is covered with clear teflon film and utilizes an air system incorporating both supply and exhaust blowers. Air is introduced along one end of an inflatable teflon panel which covers the entire chamber top. The panel is perforated on the lower side with 0.6-cm holes spaced approximately 7.6 cm apart. When inflated by air supplied to the chamber, the upper and lower surfaces of the panel form an approximately 10-cm deep envelope within which air is mixed and directed downward uniformly to the test plants in the chamber below. Air is simultaneously removed from the chamber through a peg-board floor covering a 20-cm deep false bottom. The exposure chamber is located within a walk-in growth chamber. A slightly negative pressure is maintained within the exposure chamber to prevent escape of SO_2 into the growth chamber.

b. Pollutant Dispensing and Monitoring

The pollutant concentration programmer utilizes a probe that follows a program line drawn on the conductive surface of a revolving program chart. The kinetics of a desired exposure regime are reproduced by scribing the program line on a chart, which is then attached to a revolving drum. A new chart is required for each new program, but the same chart may be used repeatedly.

The controller responds to a variable resistance signal from the programmer and a variable voltage output from the analyzer. The controller may be operated in any of three modes: manual, automatic, or cascade. In manual mode, the aperture of the valves may be regulated by manually selecting the desired degree of valve opening. In automatic, the desired concentration level may be preset and the system will automatically maintain that level by changing the valve apertures as needed. When rapid changes in concentration are required, the cascade mode is used. In cascade, the input signal is changed automatically in response to the specific program, and valve apertures are varied by the controller to produce programmed pollutant concentrations.

The valve system consists of two electropneumatic valves of unequal size that operate in parallel. The apertures of the valves are adjusted by compressed air in response to an electronic signal from the controller. The volume of flow through the system at any degree of valve opening may be increased or decreased by increasing or decreasing the pressure of the SO_2 supply.

An adjustable teflon sampling line is oriented at plant height and connected to the control system module located outside the growth chamber. Wrapping the tubing with heating tape reduced its equilibration time and eliminated absorption problems caused by condensation of water within the tubing.

c. Environment Controls

The programmable light, temperature, and relative humidity controls on the walk-in growth chamber are adjusted to provide desired conditions within the exposure chamber.

d. Data Acquisition

Sulfur dioxide concentrations are recorded and compared with the programmed exposure kinetics.

2. Performance Evaluation

a. Pollutant Uniformity

When the sample probe was rotated around a circle within the chamber, fluctuations in concentrations were not detectable at 4.0 ppm and were less than 0.01 ppm at an internal SO_2 level of 0.70 ppm.

b. Environment Uniformity

Not described.

c. Pollutant Control and Maintenance

Criteria for control of rapidly changing SO_2 concentrations were met. High concentrations could be produced rapidly within the chamber (0 to 4.5 ppm in less than 2 min), and flushing time was minimal (4.5 to 0.1 ppm in less than 3 min). Abrupt manual changes in valve aperture could be seen as recorder deflections in 30 to 60 seconds. Recorder responses to rapid changes in concentrations were smooth, indicating that mixing was thorough. With the controller in the cascade mode there was a 1- to 2-minute lag time in reproduction of programmed concentrations when program slopes were steep, but the conformation of typical field exposures could be closely reproduced. Comparison of programmed and reproduced exposure kinetics revealed an accurate reproduction of individual program peaks, short-term averages, and the total exposure dosage. The principal shortcoming of this sytem is that, in the cascade mode, the controller will maintain a valve opening of not less than 10% even when the programmer calls for less.

d. Environment Control and Maintenance

Not described.

e. Chamber Equilibration

Described in (c) above.

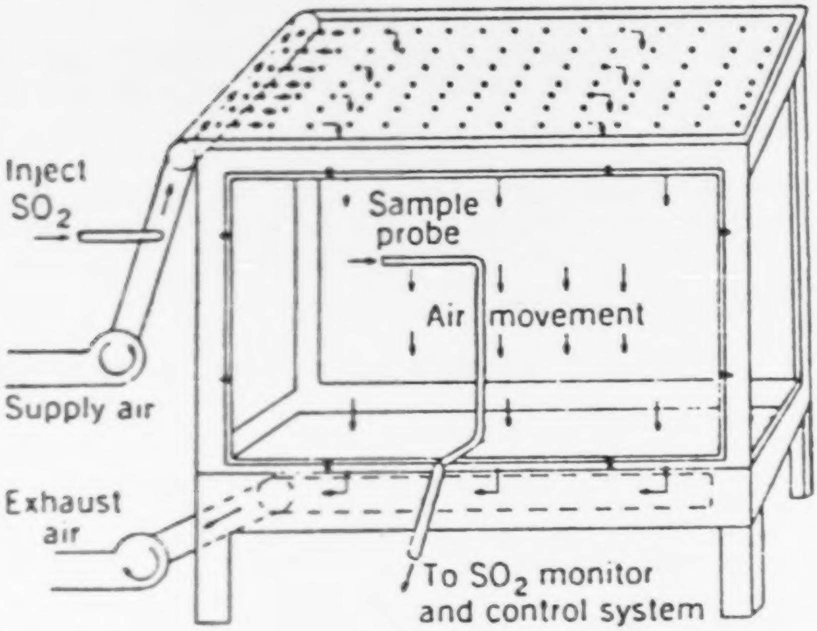


Figure E-6. Diagram of exposure chamber showing single-pass air flow system required for control of rapidly changing internal pollutant concentrations. (Note double-walled teflon envelope on chamber top.) Employed in sulfur dioxide exposures (reprintd from McLaughlin et al., 1976, with permission of the Air Pollution Control Association).

Publication: Menser, H. A., and H. E. Heggestad. 1964. A facility for ozone fumigation of plant materials. Crop Sci. 4:103-105.

Location: Agricultural Research Service, U.S. Department of Agriculture, Beltsville, Maryland

Summary: A plant fumigation chamber used for ozone studies is described. The installation consists of an ozonizer, an activated-charcoal air filter, and an exposure chamber. A walk-in refrigerator is equipped with fluorescent lights, and provisions are made for control of temperature, relative humidity, and air flow rate.

1. Hardware

The principal components and accessory equipment are a large-capacity ozonizer, an activated-charcoal air filter, and a fumigation chamber.

a. Chambers

The fumigation chamber is a modified walk-in type refrigerator equipped with overhead lighting and provisions for control of temperature, relative humidity, and air movement.

b. Pollutant Dispensing and Monitoring

Filtered air and ozone pass into the chamber through ducting.

c. Environment Controls

Fluorescent lamps are mounted below the chamber ceiling. Chamber temperature is regulated by a thermostatically controlled refrigeration unit and circulating fan. Humidity is increased by using vaporizing nozzles.

d. Data Acquisition

Temperature and humidity are recorded.

2. Performance Evaluation

a. Pollutant Uniformity

The maximum difference across the plant area was about 0.025 ppm when the chamber was operated at 0.25 ppm. Slight changes in ozone were thought to be due to temperature cycling.

b. Environment Uniformity

Temperature fluctuated about 1°C during fumigations. Relative humidity fluctuated from 5 to 10% during temperature cycling.

c. Pollutant Control and Maintenance

Ozone concentrations between 0.06 and 1.00 ppm were generated readily.

d. Environment Control and Maintenance

Not described.

e. Chamber Equilibration

Not described.

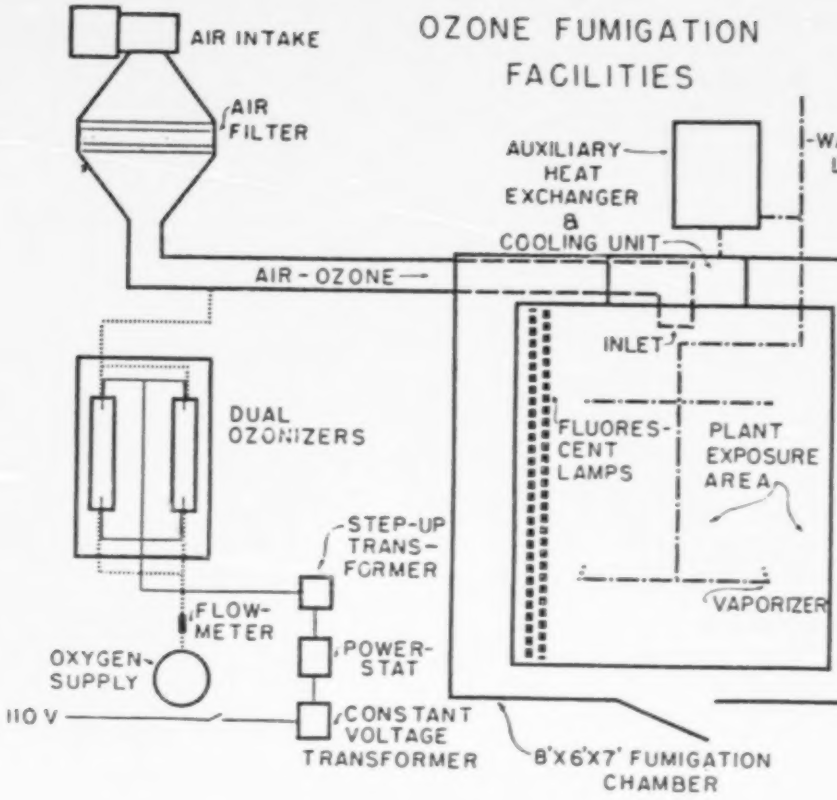


Figure E-7. Design and arrangement of controlled environment chamber for ozone research (reprinted from Menser and Heggestad, 1964, with permission of Crop Science Society of America, Inc.).

Publication: Oliva, M., and L. Steubing. 1976. Effects of H_2S fumigation on the photosynthesis, respiration, and water budget of Spinacia oleracea. Angew Botanik 50:1-17.

Location: Botany Institute, Justus-Liebig University, Giessen, West Germany

Summary: A new installation is described for fumigation with very low concentrations of H_2S under defined climatic conditions. (In German language with English summary.)

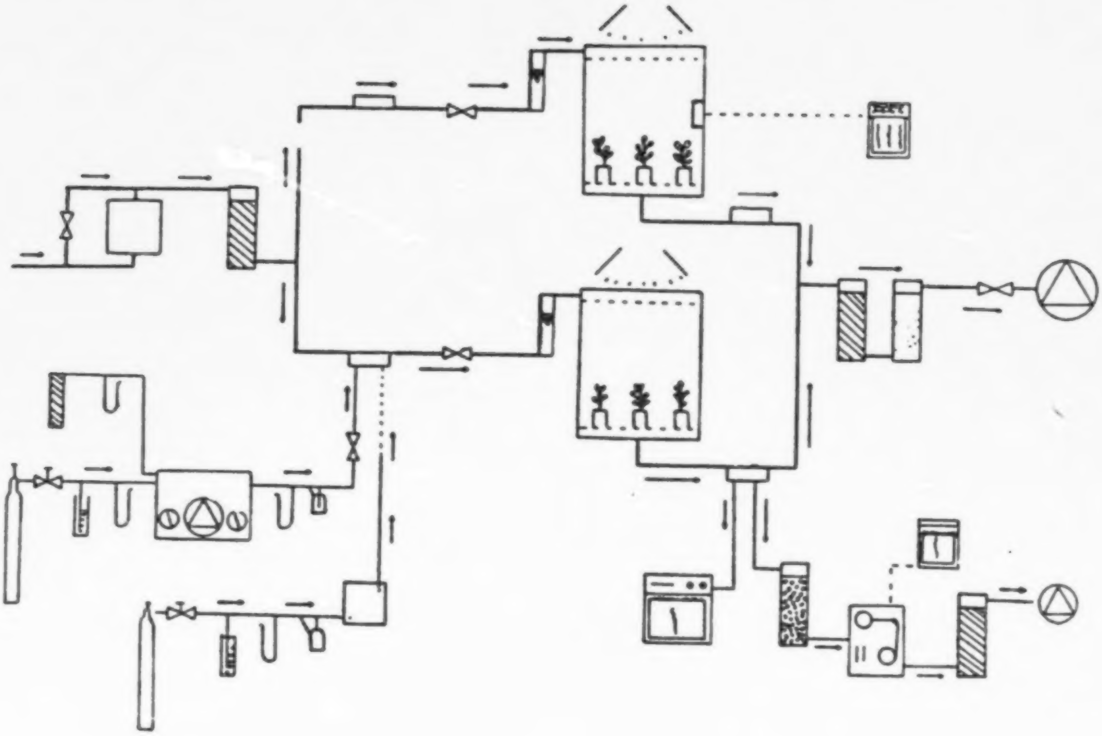


Figure E-8. Controlled environment chambers for hydrogen sulfide research (reprinted from Oliva and Steubing, 1976, with permission of the author).

Publication: Payer, H. D., L. W. Blank, G. Gnatz, W. Schmolke, P. Schramel, and C. Bosch. 1986. Simultaneous exposure of forest trees to various pollutants and climatic stress. Water, Air, Soil Pollut. 31:485-491.

Location: Institute for Biochemical Plant Pathology, GSF, Munich, West Germany

Summary: This report describes a controlled-environment facility designed to simultaneously generate the complex climatic and pollutant conditions characteristic of field sites. The new facility consists of two environmental chambers. The technical characteristics of the facility are outlined on the basis of the design specifications and the performance during the first test under experimental conditions.

1. Hardware

The system is based on the concept of a chamber-in-chamber facility. Components include systems for lighting, air filtering and circulation, gas exposure and analysis, and monitoring and control.

a. Chambers

The two large environmental chambers have a common monitoring room but can be operated independently. Four smaller subchambers can be placed within each large chamber. Light and climatic conditions are identical for the four subchambers but gas supply and root temperature control can be varied individually. The lighting system consists of krypton, metal halide and xenon lamps, the former to simulate dawn conditions, the latter two for simulating standard daylight. A horizontal air recirculation system is used in the large chambers. Subchambers use a vertical, single-pass-through air circulation.

b. Pollutant Dispensing and Monitoring

Gases are diluted with fresh air to a preliminary concentration not acutely toxic to plants. This pre-mixture is injected into the fresh air supply of the chambers. High precision, mass flow controllers are used for mixing and dispensing. Different gas mixtures can be added to each chamber and subchamber. Air samples are taken for analyses from the unfiltered and prefiltered air, and from the chambers.

c. Environment Controls

Cooling and heating of the chambers is carried out indirectly using a brine system. Light levels up to 120 Klux may be obtained. At high light intensities, an increased air exchange and circulation rate is used to offset the greater heat load from the lights. Incoming fresh air is preconditioned for 40 to 70% relative humidity before filtration and entry into each large chamber.

d. Data Acquisition

All chambers have a central monitoring and control system for all pollutant and environmental factors.

2. Performance Evaluation

a. Pollutant Uniformity

Not described.

b. Environment Uniformity

Not described.

c. Pollutant Control and Maintenance

The chambers are capable of operating with 0.01 to 1000 mg m^{-3} of SO_2, NO_x, O_3, HC, CO_2, and other gases.

d. Environment Control and Maintenance

The temperature range is -20 to +40°C, humidity 20 to 95%, light 0 to 120 Klux, wind speed 0.05 to 0.7 m s^{-1}, and air exchange 0.5 to 4 chamber volumes per minute.

e. Chamber Equilibration

Not described.

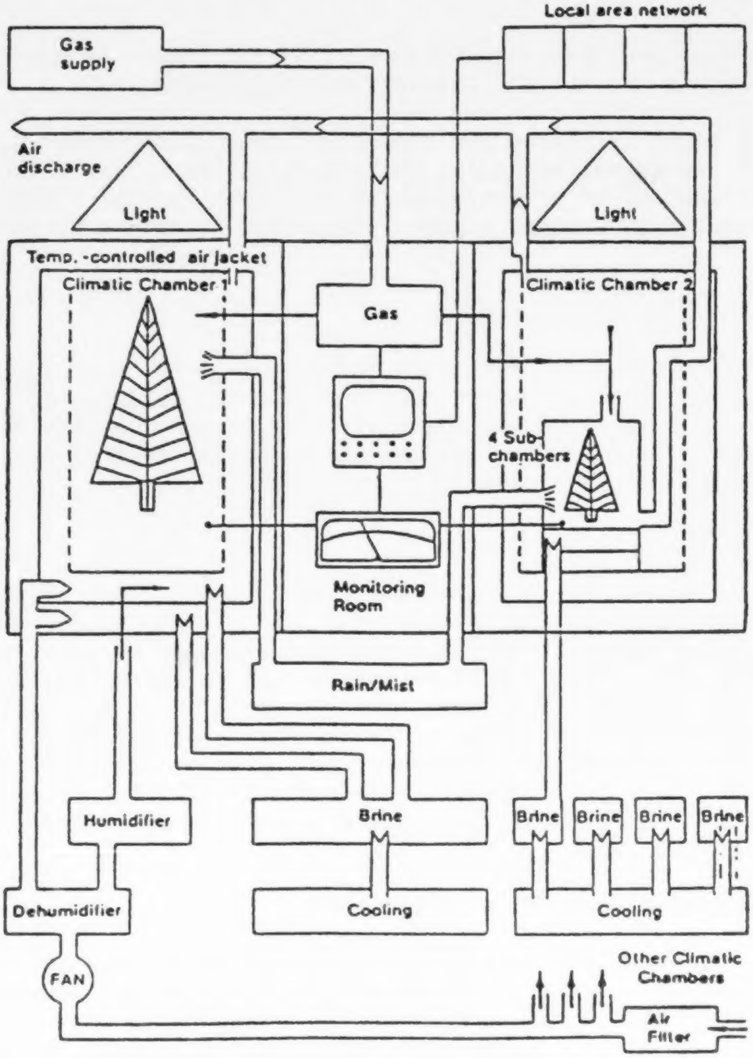


Figure E-9. Technical design of controlled environment chambers for air pollution research (reprinted with permission of H.-D. Payer).

Publication: Rogers, H. H., H. E. Jeffries, E. P. Stahel, W. W. Heck, L. A. Ripperton, and A. M. Witherspoon. 1977. Measuring air pollutant uptake by plants: A direct kinetic technique. J. Air Pollut. Contr. Assoc. 27:1192-1197.

Location: Agricultural Research Service, U.S. Department of Agriculture, North Carolina State University, Raleigh, North Carolina

Summary: This paper describes the design of a chemical reactor system suitable for plant growth and exposure, while meeting the criteria necessary to apply the concept of a continuous stirred tank reactor (CSTR). This system was the forerunner of the CSTR system described by Heck et al. (1978).

1. Hardware

The complete CSTR plant exposure system consists of two cylindical chambers. There is a common inlet and separate outlets for the two chambers. Flow through the system is maintained by a pump on the downstream side. The chambers are mounted on a cart that is wheeled into a controlled environment room.

a. Chambers

The cylindical chambers are each of 200-liter volume and arranged side by side on a cart. All internal surfaces are made of teflon or glass to minimize reaction and loss of gases to surfaces. Plants are placed inside by lifting the chambers from their gasketed bases. Welded steel frames are commercially coated with teflon. Circular steel bands and rubber gaskets hold the teflon film to the frame. Teflon-coated impellers are motor-driven from the lower level of the cart. Inlet and outlet manifolds are fabricated from glass tubing. Flow through the system is monitored by rotameters with adjustable valves.

b. Pollutant Dispensing and Monitoring

The main air stream enters the system through a glass fiber filter after which the treatment gas is injected. The gas stream enters a mixing bulb and, after it is mixed, the inlet monitoring sample is taken. Sequential sampling of inlet and outlets, and subsequent delivery of samples to the monitoring instruments is controlled by solenoids. Air from the sampling points is taken continously, but only one sample is analyzed at a time; the other samples are bypassed to exhaust.

c. Environment Controls

Environmental conditions are dependant on those of the controlled-environment room in which the chambers are placed.

d. Data Acquisition

Not described.

2. Performance Evaluation

Under experimental conditions, the chamber system meets all design criteria. Data obtained from the chambers shows a high precision for the measurement of kinetic and biological processes.

a. Pollutant Uniformity

To test for uniform mixing, a tracer smoke of titanium tetroxide is used. Mixing is visually uniform with no dead areas or pluming. Uniform mixing was also verified with dynamic flow tests with nitrogen dioxide as a tracer gas. Mixing was nearly perfect and performance approximated that of an ideal CSTR.

b. Environment Uniformity

Essentially the same environment as the growth room is maintained throughout each CSTR chamber. Lighting is uniform in each chamber.

c. Pollutant Control and Maintenance

The inlet concentration of NO_2 is maintained by a dynamic technique in which the gas is injected through a stainless steel capillary for flow control from a high pressure calibration tank into the air stream. This injection system produces essentially constant NO_2 levels over extended periods.

d. Environment Control and Maintenance

The single pass flow scheme and the spectral transmission properties of teflon film prevent a large rise ($< 0.5°C$) in the temperature of air moving through the system.

e. Chamber Equilibration

The chamber essentially follows the ideal CSTR chamber with equilibrium reached in 6.6 residence times which was between 120 and 130 minutes for this particular system.

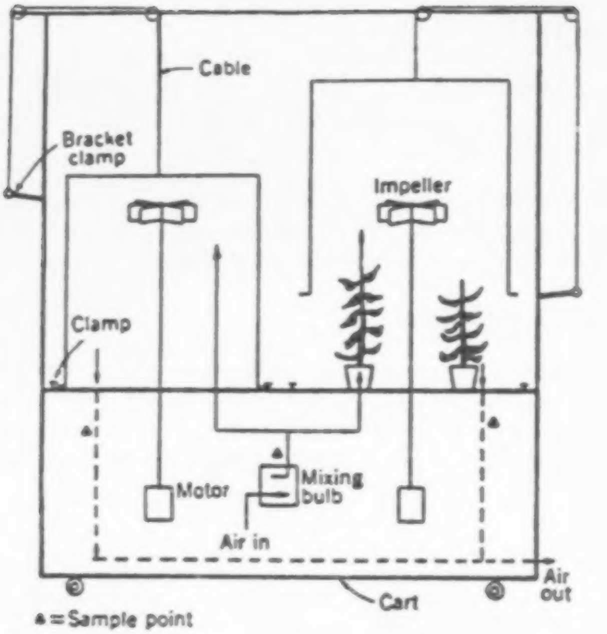


Figure 1. Schematic diagram of dual CSTR system.

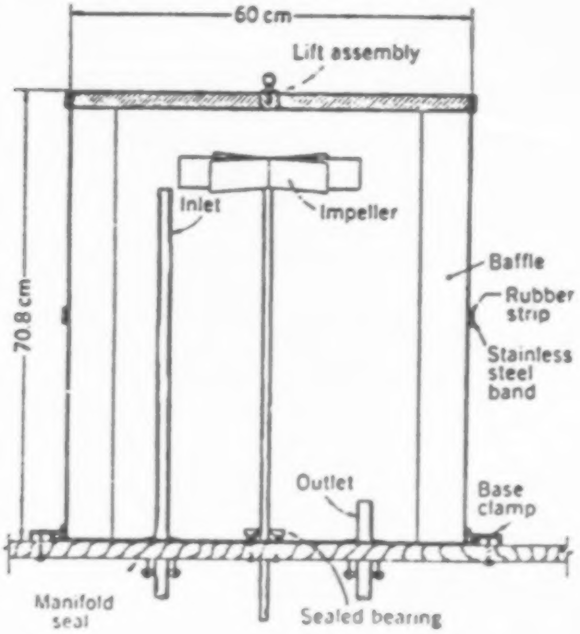


Figure E-10. Schematic diagram of dual CSTR system (A) and cross-sectional view (B) of CSTR for air pollutant uptake research (reprinted from Rogers et al., 1977, with permission of the Air Pollution Control Association).

Publication: Wood, F. A., D. B. Drummond, R. G. Wilhour, and D. D. Davis. 1973. An exposure chamber for studying the effects of air pollutants on plants. Penn. State Univ. Prog. Rep. 335. University Park, Pennsylvania. 7 pp.

Location: Department of Plant Pathology, Pennsylvania State University, University Park, Pennsylvania

Summary: To study the effect of photochemical air pollutants (e.g., ozone and PAN) on plants, a commercial plant growth chamber was selected that had precise temperature and relative humidity control and was large enough to accommodate 5- to 10-year-old trees. The chamber was modified to provide a uniform concentration of fumigant throughout its interior, and interior components were treated or modified to prevent corrosion by oxidants.

1. Hardware

The facility consists of a plant growth chamber modified for exposure studies.

a. Chambers

The exposure chamber has two major components, the control console and the chamber proper. The system includes a light cap separated from the interior of the chambers by a plexiglass barrier, highly reflective stainless steel and mylar-faced aluminum interior surfaces, air flow from ceiling to floor, and a vertically adjustable plant bed. Modifications for exposure studies with ozone and PAN included coating interior surfaces with epoxy base paints, installation of teflon-insulated wiring, and sealing of leaks. An air exchange system, access ports, and a system for introducing pollutants were installed.

b. Pollutant Dispensing and Monitoring

Air carrying the introduced pollutant moves downward over the plants with some air continously removed near the ceiling. The pollutant is introduced into the end walls of the chamber at six different points, where it mixes with charcoal-filtered air. The nature of routine monitoring is not described.

c. Environment Controls

Control features include a system for controlling temperature and relative humidity jointly, with possible interlocking with light.

d. Data Acquisition

Temperature and humidity data are recorded on a multi-point recorder. Data acquisition for pollutant concentrations is not described.

2. Performance Evaluation

a. Pollutant Uniformity

Uniformity and control of pollutant concentration was evaluated by injecting O_3 into the system and measuring concentrations at eight different points along the long-control axis at five different heights above the plant bed and at 24 points in a horizontal plane 36 cm above the plant bed. The O_3 concentration fluctuated in the vertical plane by a maximum of ± 0.5 pphm at 7 to 9 pphm or approximately 5% and by a maximum of ± 1.0 pphm at 27 to 29 pphm or approximately 5%. Similar fluctuations occurred in the horizontal plane.

b. Environment Uniformity

Uniformity of temperature and relative humidity were checked with the lights on, at different points along vertical and horizontal planes within the chamber. Temperature was measured with copper-constantan thermocouples connected to a strip chart recorder. Uniformity of temperature was evaluated with 24 thermocouples arranged in a horizontal plane at 41-cm intervals along the long axis of the chamber and 38-cm intervals along the short axis. During temperature regimes of 10, 16, 21, and 27°C, temperature was measured in three different horizontal planes at levels of 0, 46, and 91 cm above the plant bed. There was a 0.6 to 2.2°C increase in temperature from the front to the rear wall of the chamber interior. This pattern was most obvious at lower temperatures and at lower levels in the chamber. In most cases, the temperature did not vary by more than 1.1°C in the horizontal plane examined.

The uniformity of relative humidity was checked by measuring wet bulb temperatures at 24 points in two horizontal planes within the chamber. Thermocouples wrapped with cotton thread were used as wet bulbs. The temperature of wet bulbs was recorded with a multi-point strip chart recorder. Wet bulb temperature varied from 0.6 to 2.2°C across the chamber. Corrections for differences in wind speed across the chamber were not made and the temperature measuring and recording system had an accuracy of only ± 0.6°C.

c. Pollutant Control and Maintenance

Fluctuations in O_3 concentration with time were measured in the same manner as for the uniformity evaluation. At 10 pphm the concentration fluctuated by ± 0.5 pphm and at 50 pphm by ± 1.5 pphm. Since this is essentially a closed system with a small rate of air exchange, a steady concentration of pollutant was maintained by introducing the pollutant at the same rate at which it was destroyed or otherwise removed from the atmosphere within the chamber. There was a tendency for the concentration to increase slowly over time but this was easily corrected by periodic adjustment of the amount of pollutant entering the system.

d. Environment Control and Maintenance

Fluctuations in temperature with time (temperature control) were measured at a single point in the horizontal plane at different heights in the chamber. Temperature varied by ± 0.3° at 10°C, ± 0.4° at 16°C, ± 0.7° at 21°C and ± 0.6° at 27°C, with a periodicity of approximately 3 minutes. In general the fluctuation was lowest near the plant bed and increased with height.

Fluctuations in relative humidity at a given point for a period of time were measured with wet bulb thermocouples. Wet bulb fluctuations represented ± 1.0%, ± 1.0%, ± 1.5%, and ± 1.5% changes in relative humidity at 10°, 16°, 21°, and 27°C, at relative humidities of 53, 54, 60, and 63%, respectively. During exposures, relative humidity was measured with lithium chloride sensors accurate to ± 1.5% relative humidity and found to be within these limits.

e. Chamber Equilibration

Not described.

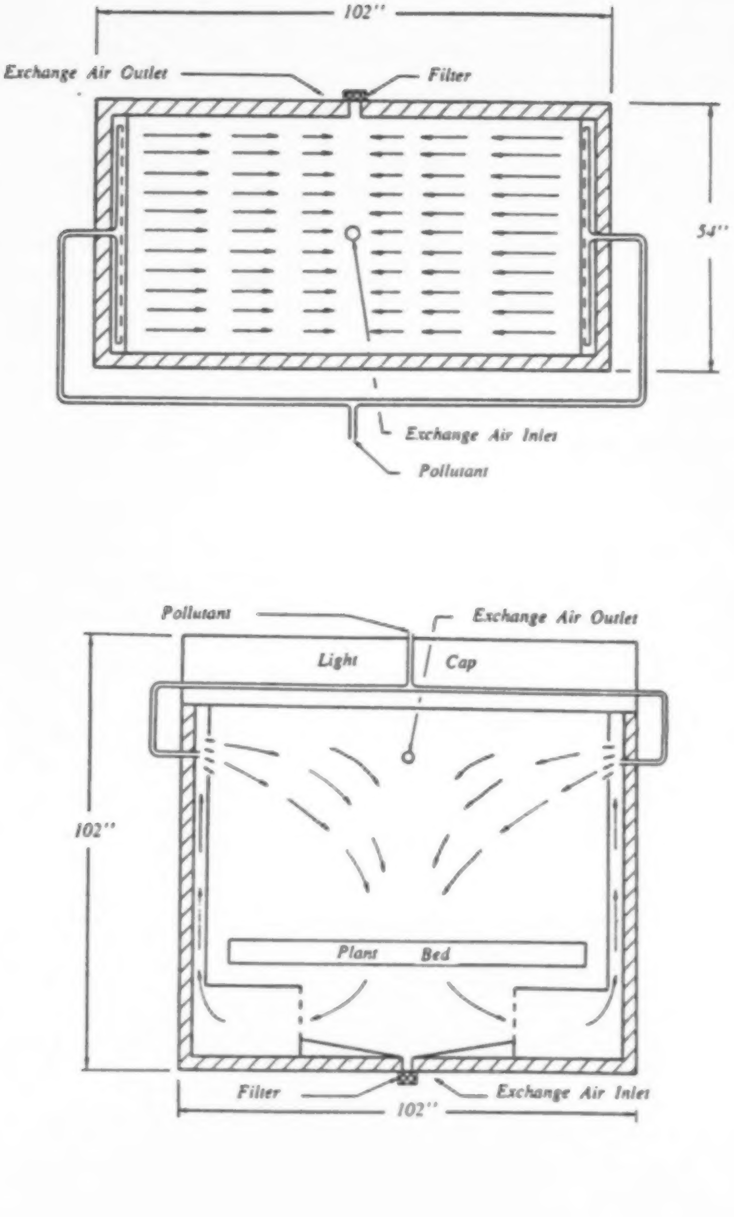


Figure E-11. Top and side views of controlled environment chamber for air pollution research (reprinted from Wood et al., 1973, Pennsylvania State University).

II. Chambers for Greenhouse Use:

Publication: Berry, C. R. 1970. A plant fumigation chamber suitable for forestry studies. Phytopathology 60:1613-1615.

Location: Southeastern Forest Experiment Station, Asheville, North Carolina

Summary: A lean-to greenhouse is used to expose potted trees to air pollutants.

1. Hardware

The greenhouse is fitted with environmental controls and a pollutant dispensing system.

a. Chamber

The lean-to greenhouse has a volume of 8.4 m^3 and can accommodate trees as tall as 2 m.

b. Pollutant Dispensing and Monitoring

Air pollutants are introduced into the chamber through tubes leading into the air duct system and monitored with automatic analyzers.

c. Environment Controls

Desired temperatures are maintained by an air-conditioner and electric strip heaters. Pneumatic mist nozzles and steam are used to keep relative humidity at specified levels. Sunlight is used for radiation.

c. Data Acquisition

Recorders are used.

2. Performance Evaluation

a. Pollutant Uniformity

Not described.

b. Environment Uniformity

Not described.

c. Pollutant Control and Maintenance

Ozone concentrations from 0.0 to 1.0 ppm and sulfur dioxide concentrations from 0.0 to 5.0 ppm can be maintained by manual adjustment of flowmeters or by a recorder-controller.

d. Environment Control and Maintenance

Temperature control can be maintained at ± 1.0°C and humidity at ± 5%. Humidities near saturation are possible when the air conditioner-compressor is not needed; above 21°C, somewhat lower humidities must be used when cooling is necessary.

e. Chamber Equilibration

Not described.

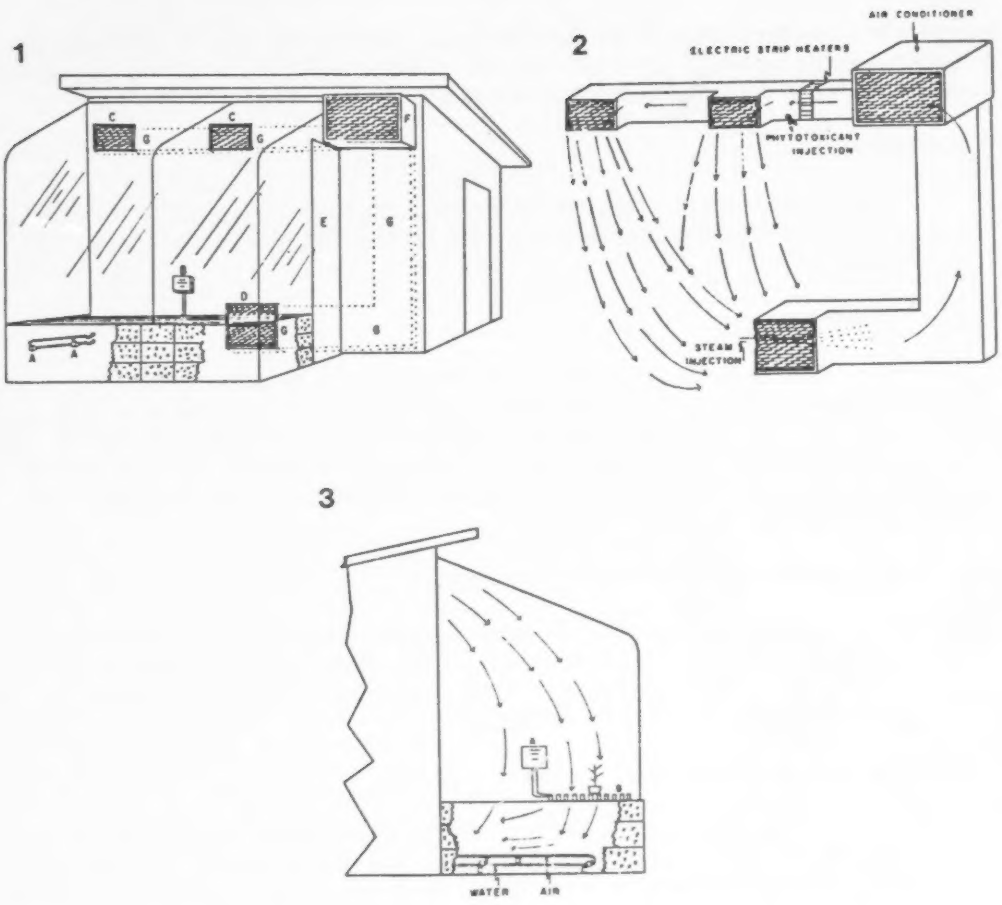


Figure E-12. Greenhouse for air pollution research. (1) Fumigation chamber: (A) pneumatic nozzles; (B) instrument shelter containing wet- and dry-bulb thermostats; (C) air inlet port; (D) air exit port; (E) entrance to chamber; (F) air conditioner; (G) air ducts. (2) Arrangement of air duct system to the chamber. (3) Side view of chamber: (A) instrument shelter; (B) bench; (C) pneumatic nozzles; and (D) air and water supply lines. Arrows indicate air flow (reprinted from Berry, 1970, with permission of the American Phytotoxicological Society).

Publication: Hill, A. C., L. G. Transtrum, M. R. Pack, and A. Holloman, Jr. 1959. Facilities and techniques for maintaining a controlled fluoride environment in vegetation studies. J. Air Pollut. Contr. Assoc. 9:22-27.

Location: Agricultural Department, U.S. Steel, Provo, Utah

Summary: This report describes greenhouses, equipment and techniques developed to study the effects of fluoride on plants, with care being exercised to maintain conditions comparable to those in the field.

1. Hardware

The facility consists of three greenhouses equipped with air conditioning and portable chambers for isolating individual plots within the greenhouses.

a. Chambers

The greenhouses are 11 m long by 2.8 m wide and 2.5 m high. Incoming air is filtered and circulated through the greenhouses at two air changes per minute. Portable chambers are of two different sizes. They are constructed of plastic sheeting over aluminum frames. The height of the larger chambers can be extended to accommodate trees.

b. Pollutant Dispensing and Monitoring

Gaseous fluoride is injected into the air stream entering a greenhouse or portable chamber. The rate of introduction is calculated for a particular air flow rate. Air in the chambers is sampled continuously for fluoride analysis.

c. Environment Control

Solar radiation heating of the greenhouse is offset by a cooling system in the incoming air ducts. The temperature and humidity in the portable chambers are maintained by using rapid air circulation.

d. Data Acquisition

Not described.

2. Performance Evaluation

a. Pollutant Uniformity

Difference in fluoride content in the air in different parts of the chamber were noted.

b. Environment Uniformity

Not described.

c. Pollutant Control and Maintenance

The fluoride concentration in the air within a chamber was found to be less than that of the incoming air because of absorption by the plants and adsorption by the walls and soil.

d. Environment Control and Maintenance

The cooling system prevents the temperature from going more than 2 to 3°C above the outside temperature during the warmest months of the year.

e. Chamber Equilibration

Not described.

Publication: Lockyer, D. R., D. W. Cowling, and L. H. P. Jones. 1976. A system for exposing plants to atmospheres containing low concentrations of sulphur dioxide. J. Exp. Bot. 27:397-409.

Location: Grassland Research Institute, Hurley, England

Summary: A description is given of the construction and operation of a system of chambers in which plants can be grown in filtered air, with or without the addition of SO_2. Concentrations of SO_2 as low as 20 ug m^{-3}, which can be maintained in the chambers over prolonged periods, are monitored automatically. The plants are grown in pots containing soil and watered by remote control, allowing exposure to SO_2 for extended periods without interruption. The method of watering is based on loss of weight and gives an estimate of transpiration. The system is based on the design given by Heck *et al*. (1968) but with considerable modification.

1. Hardware

The main components of the system are: 10 chambers in which plant pots are housed and through which filtered air is passed; apparatus to supply and meter SO_2 to each chamber and water to each plant pot; and an assembly for monitoring automatically the SO_2 concentration in the chambers.

a. Chambers

The materials used are chosen to provide good transmission of heat and light to allow satisfactory plant growth and to avoid condensation of water and the consequent removal of SO_2 from the air. Materials having little capacity to adsorb, or to react with, SO_2 are selected. Each chamber is a cube built of clear acrylic sheet covered with polyester film and containing a perforated ceiling and floor. The air supply to the chambers comes through a filtration unit constructed of ABS plastic sheet and containing a nylon dust filter and granular charcoal filter. The air duct system is constructed of ABS plastic fittings and pipes. Air is drawn from the filtration unit and blown into an inlet manifold. It then passes to the top of each chamber through an inlet duct and diaphragm valve. From beneath the floor of the chamber the air is drawn through a flowmeter and diaphragm valve to an outlet manifold, evacuated by a second blower. The apparatus for supplying water to the plant pots avoids opening the chamber and allows water use by the plants to be measured. Water is supplied via nylon tubing under pressure from a nitrogen cylinder. Each pot is mounted on a small, toploading balance.

b. Pollutant Dispensing and Monitoring

Supply of SO_2 to each chamber from a gas cylinder and manifold containing an $SO_2:N_2$ mixture is controlled by a flowmeter and injected through a hypodermic needle inserted into the inlet duct that contains a fast moving, turbulent air stream. Mixing occurs in the duct and above the perforated ceiling.

Two systems are used to monitor the SO_2 concentrations. Each system is independent and involves the continuous, sequential sampling of the chambers and of two other sites which are respective sources of air containing a known amount of SO_2 and of specially filtered air, free of SO_2.

c. Environment Controls

The system is housed in a greenhouse with automatic heating and ventilation. The filtration unit and the blowers are mounted outdoors. Supplementary lighting is provided by a single lamp mounted above each chamber. There are no additional environmental controls incorporated into the system.

d. Data Acquisition

Not described.

2. Performance Evaluation

a. Pollutant Uniformity

Using a chamber without plants but receiving 50 ug m^{-3} SO_2, samples of air were withdrawn from above the ceiling, i.e., the normal sampling point; from the center and four corners of the main compartment; and from beneath the false floor. No differences were detected among these samples indicating that thorough mixing of the added gas occurs and that it is uniformly distributed within the chamber. In a similar study, but with plants included, no depletion of SO_2 could be detected within the chamber.

b. Environment Uniformity

Not described.

c. Pollutant Control and Maintenance

Not described.

d. Environment Control and Maintenance

An experiment is reported in which the temperature range was 13.5 to 23.0°C and humidity range from 46 to 92% over the course of the experiment.

e. Chamber Equilibration

Not described.

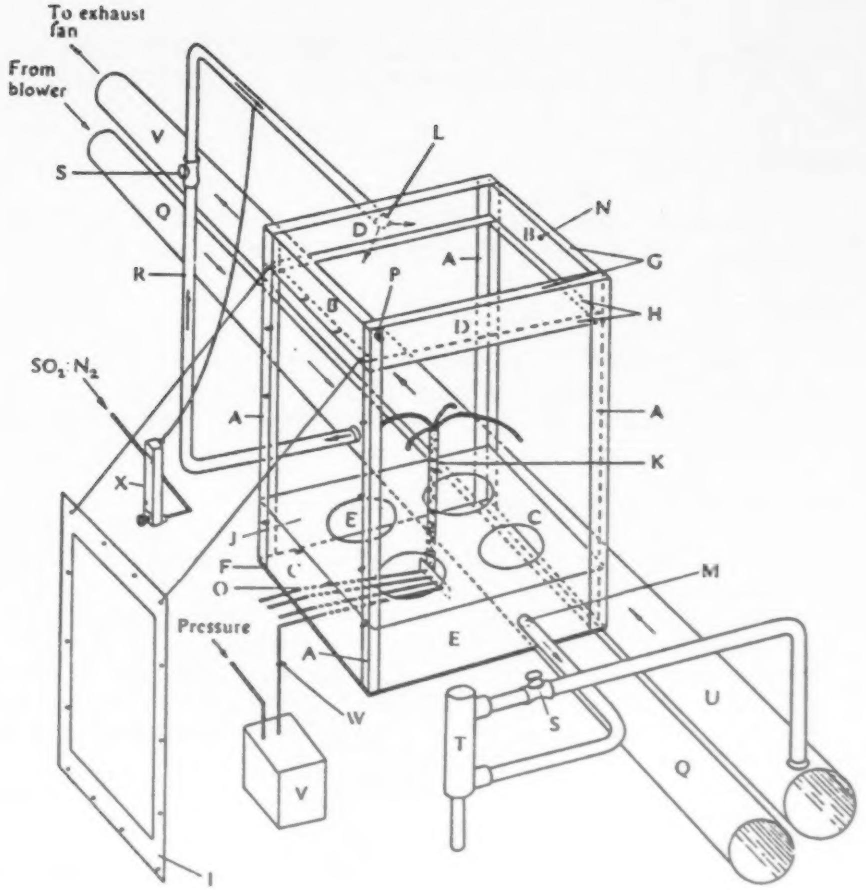


Figure E-13. Diagram of a chamber showing air, water, and SO_2 supply assemblies. Key: Arrows indicate direction of air flow. A-K = chamber components (see text); L = air inlet; M = air outlet; N = sampling port; O = water supply ports; P = auxiliary port. Air supply components: Q = inlet manifold; R = inlet duct; S, S' = diaphragm valves; T = flowmeter; U = outlet manifold; V = water reservoir; W = stop-cock; X = SO_2 flowmeter (reprinted from Lockyer et al., 1976, with permission of Oxford University Press).

Publication: Piersol, J. R., and J. J. Hanan. 1975. Effect of ethylene on carnation growth. J. Amer. Soc. Hort. Sci. 100:679-681.

Location: Department of Horticulture, Colorado State University, Fort Collins, Colorado

Summary: Chambers are constructed in a greenhouse. Temperature and humidity are controlled in the chambers and ethylene is injected from a gas cylinder.

1. Hardware

The exposure system consisted of four chambers, electrical heating, refrigeration, and a high pressure mist system to maintain humidity.

a. Chambers

Four chambers, covered with clear vinyl plastic, were constructed in a greenhouse covered with rigid PVC panels. A constant, positive pressure was maintained in the chambers with a non-recirculating air system.

b. Pollutant Dispensing and Monitoring

A gas cylinder was evacuated and then pressurized to about 1000 psi with a diluted ethylene mixture. The gas flow was controlled by three pressure regulators and glass capillary tubes, selected to provide the desired ethylene concentration in the chambers. The mixture was injected at the inlet to each chamber. A plexiglass diffusion plate of cross-sectional area equal to the chamber provided mixing. Periodically, 50-ml samples were taken from the exhaust end of chambers.

c. Environment Controls

The controls for the single air intake to all chambers employed an electrical heating system (three stages) with two refrigeration stages, in conjunction with a high pressure mist system, to maintain temperature and humidity in the chambers.

d. Data Acquisition

Not described.

2. Performance Evaluation

a. Pollutant Uniformity

Samples taken at various heights above the chamber floors indicate ethylene concentrations occasionally differ as much as 14% from top to bottom.

b. Environment Uniformity

Temperature between chambers usually did not differ more than 1°C.

c. Pollutant Control and Maintenance

Not described.

d. Environment Control and Maintenance

Night temperatures are controlled between 11.1 and 12.8°C; day temperatures vary between 16.6 and 18.3°C.

e. Chamber Equilibration

Not described.

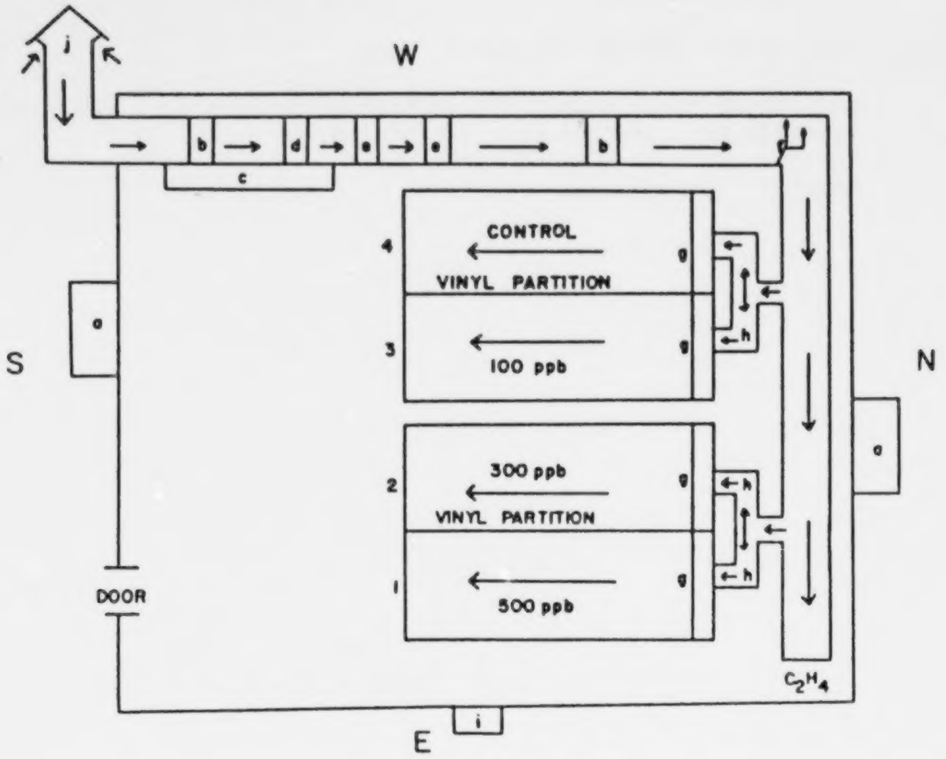


Figure E-14. Diagram of ethylene treatment chambers. a. Air-conditioning compressors. b. Fans. c. Control panel. d. Three-stage heating unit. e. Evaporators. f. Humidification unit. g. Diffusion plates. h. Point of C_2H_2 injection. i. Greenhouse exhaust fan. j. Air intake (reprinted from Piersol and Hanan, 1975, with permission of American Society of Horticultural Science).

Publication: Posthumus, A. C. 1978. New results from SO_2-fumigations of plants. VDI-Berichte 314:225-230.

Location: Research Institute for Plant Protection, Wageningen, The Netherlands

Summary: This research uses long-term fumigation greenhouses. There are two greenhouses contained within one larger greenhouse. One is ventilated with SO_2-containing air; the other with charcoal-filtered air.

1. Hardware

The hardware consists of filters, blowers and greenhouse rooms.

a. Chambers

The greenhouses have a ground area of 12 m^2, a volume of about 30 m^3 and are ventilated twice a minute. This air volume (about 90 m^3 min^{-1}) passes through a charcoal filter and moves through the greenhouses from top to bottom, coming in from a 60-cm wide nylon sack hanging in the top of the greenhouse and moves out through drains in the soil.

b. Pollutant Dispensing and Monitoring

Sulfur dioxide is injected in the air stream of one of the greenhouses from a SO_2 container through a mass-flow meter, delivering a known and constant gas stream. The SO_2 concentrations in the greenhouse are measured continuously.

c. Environment Controls

Not described.

d. Data Acquisition

Not described.

2. Performance Evaluation

a. Pollutant Uniformity

Not described.

b. Environment Uniformity

Not described.

c. Pollutant Control and Maintenance

Not described.

d. Environment Control and Maintenance

Experiments are described in which temperatures are maintained between 20 and 25°C, relative humidity between 54 and 74%, and light level between 49 and 113 watts m^{-2} with additional lighting from high pressure mercury lamps.

Diagram of system not available.

III. Chambers for Laboratory and Greenhouse Use:

Publication: Heck, W. W., J. A. Dunning, and H. Johnson. 1968. Design of a simple plant exposure chamber. U.S. Dept. of Health, Educ., Welfare. National Center for Air Pollution Control Publ. APTD-68-6. Cincinnati, Ohio.

Location: National Center for Air Pollution Control, Cincinnati, Ohio

Summary: Chambers for plant exposure studies use a dynamic, negative-pressure, single-pass flow system with uniformity of toxicant flow, mixing, and distribution in the chamber. A relatively simple design permits easy installation of several chambers in a single air-handling system while still permitting individual control of chambers. The chambers can be installed in greenhouses or in controlled-environment chambers.

1. Hardware

The system consists of banks of chambers constructed with a single air-handling system.

a. Chambers

There are two chamber sizes with identical construction details. The chamber frame is wood finished with white glass enamel. The frame is covered with mylar film. The air-handling system has an exhaust blower that maintains negative pressure in the exposure chambers. Filtered air moves into the bottom of the chamber through a perforated floor. For controlled environment exposure the inlet air has controlled temperature and humidity.

b. Pollutant Dispensing and Monitoring

Pollutants are added through ports in the inlet duct from a pollutant dispensing system. The dispensing systems have an initial dilution system, so that pollutants enter the inlet duct at dilutions of about 100 to 1. Pollutant monitoring is not described.

c. Environment Controls

Greenhouse exposure chambers are normally maintained at greenhouse conditions. Two controlled-environment chambers are mounted as inserts inside each standard plant growth chamber. Temperature and humidity are initially controlled in the growth chamber and more closely controlled with each exposure chamber plenum. Light is controlled by the growth chamber and can be varied by shading one chamber. Wet- and dry-bulb thermistors are located in front of the exhaust duct of each chamber to monitor temperature and humidity.

d. Data Acquisition

Not described.

2. Performance Evaluation

a. Pollutant Uniformity

Ozone was used to evaluate operating performance of the exposure chambers. Four probes were centered vertically in each chamber within 5 cm of the four corners and a fifth was placed in the center of each chamber. Ozone concentration decreased as much as 11% with the greatest decrease at the centrally located probe with plants present. Ozone uniformity varied with environmental conditions and chamber loading. Ozone uniformity was improved by using a perforated delivery tube. Results of the uniformity test were interpreted to indicate excellent mixing within chambers of both sizes.

b. Environment Uniformity

Environmental conditions similar to those found in greenhouses exist within greenhouse exposure chambers. Under bright sunlight, the chamber temperatures ran from 2.2 to 3.3°C above greenhouse temperatures at an airflow rate of one change every 2 minutes. Measurements at several points within a chamber were consistent.

Environmental control within exposure chamber inserts inside plant growth chambers was evaluated at an air change rate of two per minute. Temperature fluctuation at a given level in the chamber was less than 0.28°C. There was a consistent difference in temperature between the top and bottom of the chamber of approximately 1.1°C at a chamber temperature of 21°C. At higher temperatures the difference was less. At any given location no temperature or humidity variations could be picked up by using a wet-bulb, dry-bulb thermistor sensing device.

c. Pollutant Control and Maintenance

Not described.

d. Environment Control and Maintenance

Not described.

e. Chamber Equilibration

Only the rate of chamber equilibration after starting or stopping pollutant flow into the chambers was evaluated. The equilibration rate after starting the dispensing system and the decay rate after stopping the dispensing system are the same, about 8 minutes under the conditions of the test.

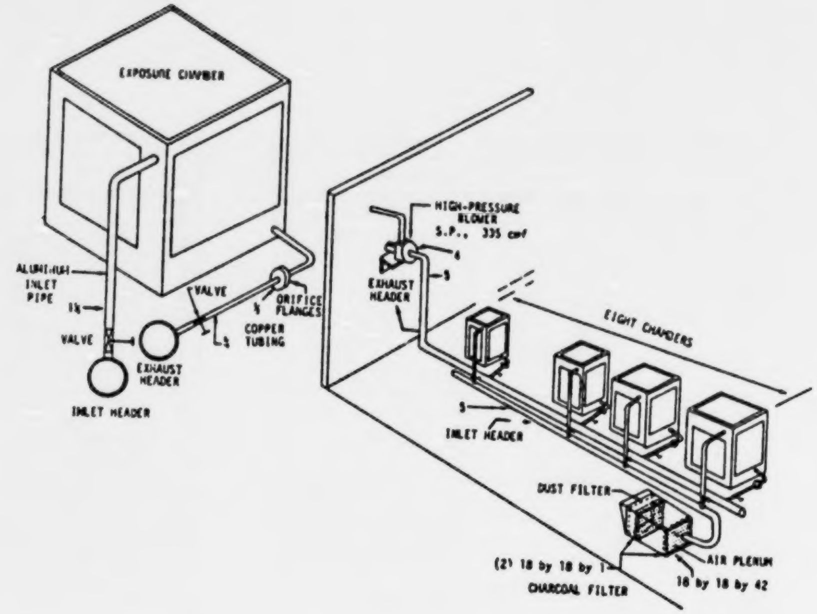
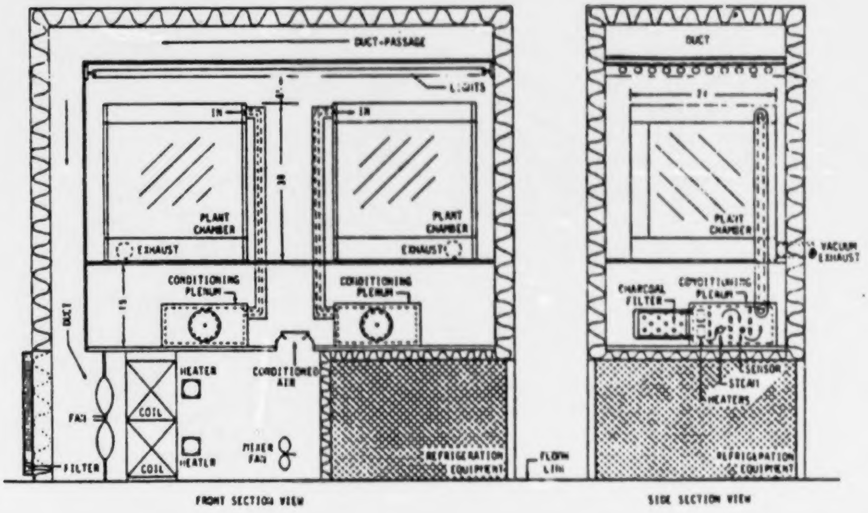


Figure E-15. Schematic showing general orientation and construction of exposure chambers in greenhouse (all dimensions shown are in inches) (reprinted from Heck et al., 1968, National Center for Air Pollution Control).



Reproduced from best available copy.

Figure E-16. Schematic showing two exposure chambers with conditioning plenums inside a plant growth chamber, front and side views (all dimensions shown are in inches) (Heck et al., 1968).

Publication: Heck, W. W., R. B. Philbeck, and J. A. Dunning. 1978. A continuous stirred tank reactor (CSTR) system for exposing plants to gaseous air contaminants. Principles, specifications, construction, and operation. Agric. Res. Serv., U.S. Dept. Agric. Publ. ARS-S-181. New Orleans, Louisiana.

Location: Agricultural Research Service, U.S. Department of Agriculture, North Carolina State University, Raleigh, North Carolina

Summary: Detailed descriptions are provided for the construction and operation of exposure chambers that use the principle of the continuous stirred tank reactor (CSTR). A CSTR system for greenhouse use consisting of nine chambers and one for controlled environment rooms of four chambers is described.

1. Hardware

The system employs a pollutant (gas) dispensing unit for control of the test chemical(s), CSTR exposure chambers, and a shared-time gas-monitoring unit.

a. Chambers

The response of plants to gaseous air pollutants is studied in a uniformly-mixed cylindrical exposure chamber (reactor) within a system that utilizes a dynamic, negative-pressure, single-pass airflow for maintenance of plants. Uniform mixing within the chamber is kept constant, regardless of air inlet velocity, by a rotating impeller. Several pollutants can be injected at once. A number of chambers can be installed into a single air-handling component with individual controls for each chamber.

b. Pollutant Dispensing and Monitoring

The gas concentrations within chambers are maintained by means of dispensing units which use rotameters and flow dilution for gases or calibrated syringe pumps for liquids. The dispensing system and chambers are integrated with a shared-time monitoring unit for determination of gas (vapor) concentrations within the chambers. Rates of pollutant gas uptake, net photosynthesis, and transpiration can be determined by monitoring inlet and outlet gas streams for the pollutant, carbon dioxide, and water vapor, respectively.

The dispensing units have three components: (1) a source of gas or pollutant (high-pressure tank(s), an ozone generator, or liquid chemical(s)); (2) precision rotameters; and (3) an air-dilution component (air manifold). Teflon tubing is used throughout this unit.

The shared-time gas-monitoring unit has three components: the monitoring lines and sampling manifold, the controller (scanner), and the monitoring instruments. These components are an integral part of the complete CSTR system.

c. Environment Controls

CSTR systems for use in environmental growth rooms utilize an environmental control system designed to maintain temperature, humidity, and light levels. CSTR systems for use in a greenhouse do not have environmental controls, but they do have high-intensity lamps so that a minimum irradiance can be maintained.

d. Data Acquisition

Each monitoring instrument is attached to a recorder for continous measurement. Temperatures are measured within chambers with thermocouples attached to a 24-point temperature recorder.

2. Performance Evaluation

a. Pollutant Uniformity

Performance data were gathered to determine the uniformity both within and across the test chambers. Sulfur dioxide and ozone were the test gases. Ozone was dispensed into the greenhouse chamber system and monitored by means of a chemiluminescent analyzer. Although small variations in ozone concentration were found across the chamber at a given height and vertically within the chamber, the ozone uniformity was within the accuracy of the monitoring method. Tests showed that the exhaust concentration was representative of the chamber concentration.

Bush snap bean plants were used to determine the uniformity of injury within and across the nine-chamber greenhouse system. Plants were placed at several positions in each chamber. Positional effects were not significant in an analysis of variance. The chamber-by-position interactions were tested and no interaction was found.

Bush snap beans were also used to determine the uniformity of injury within and across the four-chamber controlled environment system. There were generally no positional or chamber effects in a statisical analysis of leaf injury data.

Ozone and sulfur dioxide were studied together to see if they would react chemically in the chamber when dispensed simultaneously. Neither gas affected the concentration of the other gas in these tests.

b. Environment Uniformity

In the greenhouse chambers light intensity, temperature, and humidity were dependent upon the existing ambient conditions within the greenhouse. Results of a temperature-distribution study within a chamber showed both vertical and horizontal uniformity. On heavily overcast days, with the lights on, a small temperature increase (approx. 0.5°C) was found between the chamber inlet air and the chamber exhaust air. This difference was 1.7 to 2.8°C with increased natural light intensity. The inlet and exhaust temperatures across the nine-chamber system were within 1%, with or without supplemental lights on a cloudy day. Light intensity was uniform both across and within chambers on overcast days. When the supplemental lights are used, light variation at 18 cm height within a chamber may be as much as 6%, and across chambers as much as 3%. Variations were greater at a 60-cm height and less with lights off. The variations at 60 cm probably reflected shadow effects from structural parts of the chambers.

Airflow velocities through each of the controlled environment chamber inlet ducts were measured and set, by means of the exhaust valves, to give uniform flow. These velocities were converted to the number of air changes per minute. Sulfur dioxide was injected into each of the controlled environment CSTR chambers to confirm uniform airflows across chambers. The exhaust ducts were monitored for approximately 20 min after an equal flow of sulfur dioxide gas was dispensed into each chamber. There was a high uniformity of airflow across the four chambers.

c. Pollutant Control and Maintenance

Gas-flow settings are noted to be fairly consistent for any specific chamber concentration but to vary, especially in the greenhouse system, with light, temperature, and humidity within the greenhouse.

d. Environment Control and Maintenance

A study was conducted in the controlled environment chambers to determine the degree and limits of control for chamber temperatures. This study indicated that exposure chamber temperatures could be maintained between 18.3 and 35°C and from about 40 to 90 percent relative humidity. At the higher temperatures, the system would permit lower relative humidities.

The high-gloss white-enamel aluminum covering for each controlled chamber increased the maximum light intensity up to 25% and improved light distribution within each chamber. Differences between chambers reflected variation in lamp output. These differences were smoothed out by placing discs on some of the lamp reflector centers.

e. Chamber Equilibration

Ozone buildup and decay curves were determined for the four controlled environment chambers. These were almost identical for the four chambers. The first minute showed little buildup because of the delay inherent in the dispensing system. The design criterion of 6.6 chamber air changes to reach a 99% buildup or decay was met. Other checks have shown a 5% loss of ozone from inlet to exhaust in an empty chamber, possibly because of small leaks and sorption or reaction with wall surfaces.

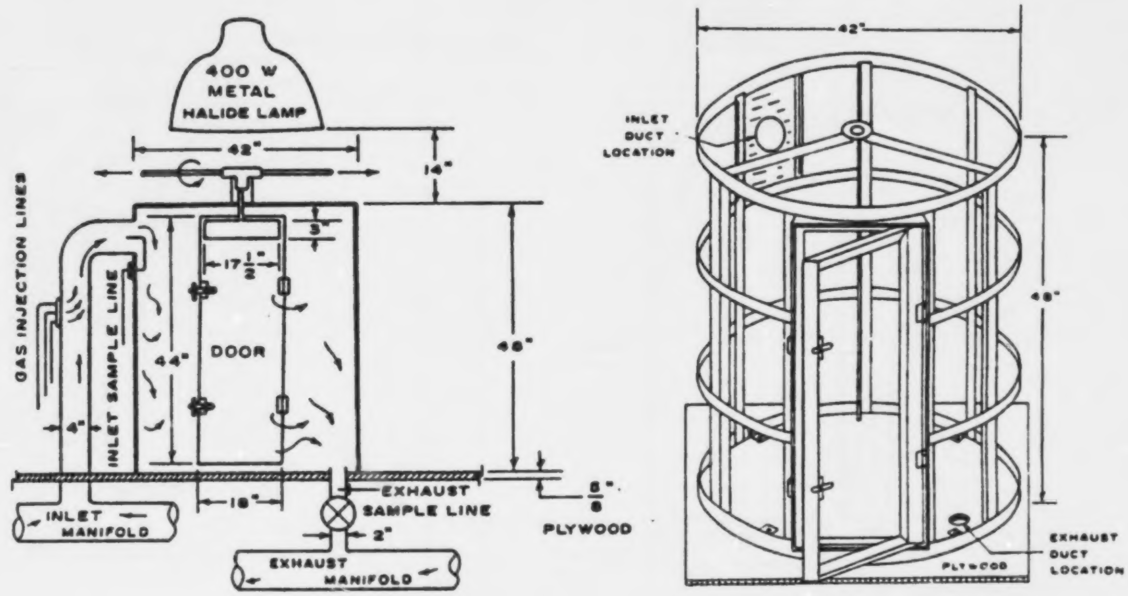
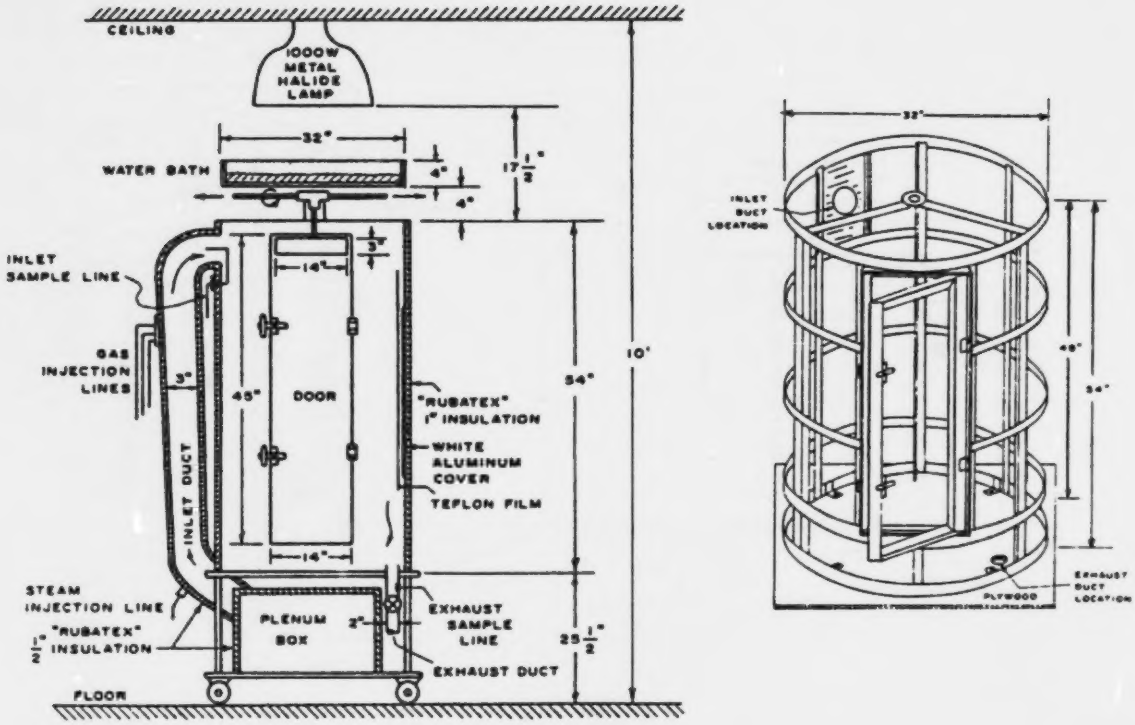


Figure E-17. Schematic of a single greenhouse CSTR chamber unit (reprinted from Heck et al., 1978).



Reproduced from best available copy.

Figure E-18. Schematic of a single phytotron CSTR chamber unit (reprinted from Heck et al., 1978).

APPENDIX F

Descriptions of Facilities and Performance Evaluations -- Systems for Rainfall Simulation Research

I. Indoors

Publication: Chevone, B. I., Y. S. Yang, W. E. Winner, I. Storks-Colter, and S. J. Long. 1984. A rainfall simulator for laboratory use in acidic precipitation studies. J. Air Pollut. Contr. Assoc. 31:355-359.

Additional Publication: Chappelke, A. H., B. I. Chevone, and T. E. Burk. 1985. Growth response of yellow-poplar (*Liriodendron tulipfera* L.) seedlings to ozone, sulfur dioxide, and simulated acidic precipitation, alone and in combination. Environ. Exp. Bot. 25:233-244.

Location: Virginia Polytechnic Institute and State University, Blacksburg, Virginia

Summary: This rainfall simulator, developed on the principal of droplet formation from needle tips, is designed for use in a glasshouse environment. Through changes in needle diameter, pump speed, and number of radial arms dispensing the solution, the system can simulate a range of physical rainfall characteristics including droplet size and rainfall intensity without sacrificing other relevant features of rainfall events. The distributional uniformity of the system is maintained by a rotating circular platform upon which pots or trays are placed. The system is suitable for studies with crops and forest tree seedlings.

1. Hardware

a. Description

Each unit is 1.6 m long, 1.0 m wide, and 2.2 m n high. The circular rotating platform has a surface area of 1.1 m^2 and is positioned 1.7 m below the dispensing system. The platform revolves at a speed of 2 rpm. The effective target area on the platform is 1.06 m^2. The system consists of four independently-operated units.

b. Methodology

(1) Dispensing

Rainfall solutions are under pressure from a variable speed pump and delivered to the radial arms of the hub containing hypodermic syringes (gauges 20, 21, and 22) positioned on the underside of each arm in a distribution providing for uniform delivery of solution. Although automation is not discussed, the system is amenable to a programmed controller providing regulated delivery according to desired rainfall intensity.

(2) Chemical Analysis and Application Rate

Methods for evaluating the concentrations of assorted cations, anions, pH, and solution conductivity are outlined for both in-line rain solutions and deposited rainfall. Application rate in the methods paper is assessed by distributing beakers on the platform.

(3) Protocol for Chemical/Temporal Exposure Dynamics

Chemical composition of rainfall is based on reported mean electrolyte concentrations in rainwater as reported over a 4-year period in southwestern Virginia. Temporal features of rainfall application are at the discretion of the experimental design. The typical protocol is a constant inter- and intra-event exposure regime.

c. Environment Controls

The environmental conditions are dictated by the glasshouse environment, which is equipped with charcoal filtration, temperature regulation, and photoperiod adjustment.

d. Data Acquisition

Not described.

2. Performance Evaluation

a. Wet Deposition

Incident hydrometeor diameter range of 2.5 to 3.4 mm with 2.7 to 3.1% coefficient of variation; mean droplet velocity = 60 to 70% of terminal velocity. Distribution statistics: coefficient of variation within a unit = 2 to 8.3%; among units = 1.2 to 2.6%. Exposure dynamics: 0.75 cm h^{-1} for 1-h event, 2 times wk.

b. Wet Deposition Environment

Not described.

c. Non-Exposure Growth Environment

Radiation and temperature reported.

d. Deposition Parameters

Chemistry of deposition calculated.

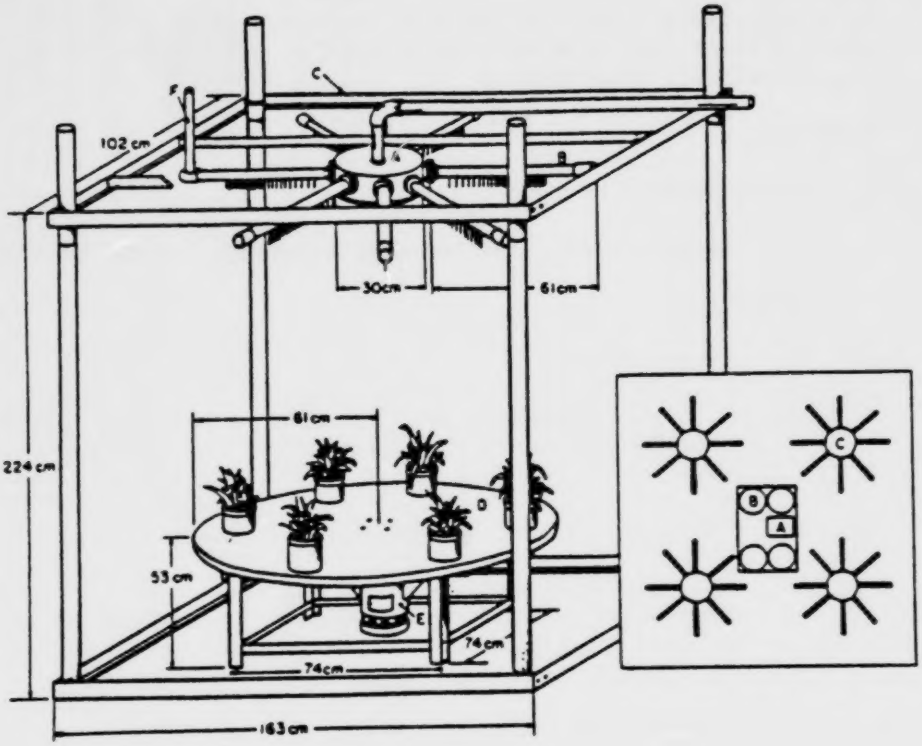


Figure F-1. Schematic diagram of a rainfall simulation unit: (a) central hub; (b) radial tubes containing hypodermic needles; (c) structural supports; (d) rotating table; (e) 1/20-hp gear motor; (f) tube indicating hydrostatic pressure. Inset: schematic aerial view of entire rainfall simulator system: (a) peristaltic pump; (b) carboy containing rain solutions; (c) an individual rainfall simulation apparatus (reprinted from Chevone et al., 1984, with permission of the Air Pollution Control Association).

Publication: Irving, P. M. 1985. Modeling the response of greenhouse-grown radish plants to acidic rain. Environ. Exp. Bot. 25:327-338.

Location: Argonne National Laboratory, Argonne, Illinois

Summary: This system is designed for use in a glasshouse environment in which the principal focus is the mechanism underlying the treatment effects on productivity of low stature plants. The environmental conditions for growth and rainfall addition are either controlled or accounted for in the experimental design (i.e., micro-climate effects in the glasshouse). Rainfall simulation is provided by stainless steel nozzles facing upward, which deliver rain to plants maintained on a turntable to assure uniformity in rainfall distribution.

1. Hardware

a. Description

Data on dimensions and specifications are not reported.

b. Methodology

(1) Dispensing

Rain simulants are dispensed by full jet nozzles that produce a median drop volume of 1.1 mm. The degree of automation is not reported.

(2) Chemical Analysis and Application Rate

Chemical analysis of pH and conductivity is conducted on each batch or stock solution and on the actual deposited rainwater. The application rate is calculated assuming a uniform distribution of rainfall delivered to the system.

(3) Protocol for Chemical/Temporal Exposure Dynamics

The chemistry of the rain simulant is based upon the weighted-average ion concentration for National Acid Deposition Program (NADP) sites in Pennsylvania, Ohio, and New York. The pH of these solutions is adjusted using sulfuric and nitric acids in the ratio reported by NADP (2.37:1). Individual rainfall events are 1 hour in duration but are applied in ten, 6-min on-off periods, producing a final rate of 0.76 cm h^{-1}. The time between rain events is 2 to 3 days.

c. Environment Controls

The glasshouse environment was monitored and/or controlled with respect to temperature, vapor pressure, photoperiod, and photoperiod intensity.

d. Data Acquisition

Not described for the wet deposition component.

2. Performance Evaluation

a. Wet Deposition Event

pH and conductivity are measured; other variables are calculated. Median droplet diameter is 1 mm. A turntable method is used with constant intra-event exposure.

b. Wet Deposition Environment

Not described.

c. Non-Exposure Growth Environment

Only radiation and temperature described.

d. Deposition Parameters

Deposition rate to soil calculated.

Diagram of system not available.

Publication: Jacobson, J. S., J. Troiano, and L. Heller. 1985. Stage of development, responses, and recovery of radish plants from episodic exposure to simulated acidic rain. J. Exp. Bot. 36:159-167.

Additional Publication: Troiano, J., and E. J. Butterfield. 1984. Effects of simulated acidic rain on retention of pesticides on leaf surfaces. Phytopathology 74:1377-1380.

Summary: This is a glasshouse system designed to investigate the influence of rainfall chemistry on specific plant processes under well-controlled environmental conditions. The system administers rainfall through nozzle injection of solutions to plants positioned on a turntable to assure uniformity. There are four independently-operated rainfall simulators.

1. Hardware

a. Description

The turntable diameter is either 1.0 or 2.0 m and rotates at 3 rpm. One nozzle per unit is mounted 3.0 m above the turntable. Consequently, the surface area for pots is 0.78 m^2 or 3.14 m^2, and the maximum plant height (pot plus aboveground portion) is 3 m.

b. Methodology

(1) Dispensing

Rain simulant is dispensed through a stationary, hydraulic, hollow-cone nozzle positioned 3 m above the turntable. The degree of automation is not reported.

(2) Chemical Analysis and Application Rate

The method for chemical analysis is not reported. Simulated rainfall is collected on the turntable to achieve deposition rates of 1.0 cm h^{-1}.

(3) Protocol for Chemical/Temporal Exposure Dynamics

The chemistry of the rainfall is based on reported concentrations of cations and anions in the MAP3S network taken near Ithaca, New York, during the growing season. The acidity of the solution is adjusted using sulfuric and nitric acids in a 2:1 ratio. Rainfall events are pre-scheduled according to the experimental design with most events lasting 1 h.

c. Environment Controls

The glasshouse environmental conditions are monitored and/or controlled for photoperiod, temperature, irradiance during photoperiod extension, and vapor pressure.

d. Data Acquisition

Not described.

2. Performance Evaluation

a. Wet Deposition Event

Concentrations of the incident hydrometeor were calculated. Droplet size diameter ranges from 200 to 500 um. Coefficient of variation for deposition = 20% on the turntable. A constant intra-event time is employed.

b. Wet Deposition Environment

Not reported.

c. Non-Exposure Growth Environment

Only radiation and temperature reported.

d. Deposition Parameters

Deposition to soil has a coefficient of variation of 20%; deposition chemistry is calculated.

Diagram of system not available.

Publication: McColl, J. G., and R. Johnson. 1983. Effects of simulated acid rain on germination and early growth of Douglas fir and ponderosa pine. Plant Soil 74:125-129.

Additional Publication: Killham, K., M. K. Firestone, and J. G. McColl. 1983. Acid rain and soil microbial activity: Effects and their mechanism. J. Environ. Qual. 12:133-137.

Location: University of Berkeley, Berkeley, Calfiornia

Summary: This is an open-air rainfall simulator set up in four partitioned rooms, open to the atmosphere but sheltered from ambient precipitation. The system's air exchange is passive rather than active/forced air. The experimental designs have focused on changes in both tree growth and soil properties as a function of rainfall chemistry. The influence of the shelter on the radiant and heat energy properties of the system are not reported.

1. Hardware

   a. Description

      Dimensions and specifications are not reported.

   b. Methodology

      (1) Dispensing

         Not described.

      (2) Chemical Analysis and Application Rate

         The method for estimating deposition rates is inferential (i.e., calculated based on delivery of solution to a given surface area). Methods for chemical analysis are not reported except for the pH of the rain simulant.

      (3) Protocol for Chemical/Temporal Exposure Dynamics

         The chemical composition of the rain simulant is based on the average rainfall chemistry in northern California with pH adjustment being achieved through addition of sulfuric and nitric acid. The frequency of application is twice weekly at a rate based on that reported in California. The temporal exposure dynamics (i.e., time of day, duration of event, frequency between events) are not reported.

   c. Environment Controls

      Reported only for soil properties.

d. Data Acquisition

Not described.

2. Performance Evaluation

a. Wet Deposition Event

Calculated chemistry of stock solution.

b. Wet Deposition Environment

Not described.

c. Non-Exposure Growth Environment

Soil solution chemistry reported.

d. Deposition Parameters

Deposition to soil reported but methods not defined.

Diagram of the system was not available.

Publication: Raynal, D. J., J. R. Roman, and W. M. Eichenlaug. 1982. Response of tree seedlings to acid precipitation. II. Effect of simulated acidified canopy throughfall on sugar maple seedling growth. Environ. Exp. Bot. 22:385-392.

Location: State University of New York, Syracuse, New York

Summary: This system consists of a single treatment chamber constructed of wood framing and covered with polyethylene sheeting. Rain nozzles are mounted in each corner, and solutions are injected toward the center of the exposure area. Potted seedlings are manually repositioned on the platform to maximize deposition uniformity. The system is suitable for either crops or tree seedlings of low stature. The most unique feature of the research is the selection of the simulant chemistry to represent that occurring in throughfall rather than incident precipitation, which is a legitimate method to address the issue of how acidified rainfall (after it is chemically processed by passage through the canopy) may influence seed germination and early seedling growth. Both of these biological processes take place on the forest floor so that the chemistry of the bulk of the wet deposition to the forest floor is more characteristic of throughfall than incident rainfall.

1. Hardware

   a. Description

      The single unit is 1 m wideby 1 m in long by 1.5 m high. The surface area for growing plants is 1 m^2, while the maximum height to assure even rainfall deposition is not reported.

   b. Methodology

      (1) Dispensing

         Rainfall simulants under pressure are dispensed with nozzles facing upward. Methods of automation are not reported.

      (2) Chemical Analysis and Application Rate

         The chemical analysis methods are not reported. The rainfall application rate is estimated.

      (3) Protocol for Chemical/Temporal Exposure Dynamics

         The chemistry of the simulant is uniquely adjusted to match that reported for throughfall at Hubbard Brook rather than incident precipitation. The temporal aspects of application are pre-scheduled and for fixed time intervals (20-30 min). The total deposition rate is equivalent to 2.5 cm wk^{-1}.

c. Environment Controls

The conditions during rain events are defined relative to air temperature and irradiance. The environmental conditions during subsequent growth periods (i.e., photoperiod, day and night temperature, and irradiance) are monitored and controlled.

d. Data Acquisition

Not described.

2. Performance Evaluation

a. Wet Deposition Event

Data provided on stock solution recipe. Qualitative evaluation of distribution statistics.

b. Wet Deposition Environment

Only radiation and temperature reported.

c. Non-Exposure Growth Environment

Only radiation, temperature, and soil solution chemistry reported.

d. Deposition Parameter

Throughfall chemistry reported. Soil deposition chemistry and profile processing reported.

Diagram of the system was not available.

Publication: Rebbeck, J., and E. Brennan. 1984. The effect of simulated acid rain and ozone on the yield and quality of glasshouse-grown alfalfa. Environ. Pollut. (Series A) 36:7-16.

Location: Cook College, New Jersey Agricultural Experiment Station, New Brunswick, New Jersey

Summary: This is a glasshouse system designed to simulate rainfall for plants maintained in pots. The system is most suitable for low stature vegetation canopies (< 0.35 m). The environment during exposure is presumed to be equivalent to that of the growing conditions in the glasshouse.

1. Hardware

   a. Description

      Dimensions and specifications are not reported.

   b. Methodology

      (1) Dispensing

      Solutions are dispensed through four nozzles (2-mm dia.) mounted above the potted plants. Methods of automation are not reported.

      (2) Chemical Analysis and Application Rate

      Methods for chemical analysis are not reported except for solution pH. The chemical composition of the tap water (makeup water for the simulant) is reported.

      (3) Protocol for Chemical/Temporal Exposure Dynamics

      The chemistry of the rainfall simulant is adjusted to provide a range of acidities by adding concentrated sulfuric acid. The additional cations and anions are those reported for tap water concentrations. The temporal features of rainfall application are pre-scheduled, providing 2.0 cm per rain event delivered during a 15-min time period once per week.

   c. Environment Controls

      The glasshouse environment is monitored and controlled for photoperiod, temperature, and trace pollutant levels (charcoal filtration).

   d. Data Acquisition

      Not described.

2. Performance Evaluation

   a. Wet Deposition Event

      Chemistry data on makeup water only.

   b. Wet Deposition Environment

      Not described.

   c. Non-Exposure Growth Environment

      Only radiation and temperature reported. Charcoal-filtered air for glasshouse.

   d. Deposition Parameters

      Soil deposition rate calculated by inferential method.

Diagram of system was not available.

Publication: Shafer, S. R., L. F. Grand, R. I. Bruck, and A. S. Heagle. 1985. Formation of ectomycorrhizae on *Pinus taeda* seedlings exposed to simulated acidic rain. Can. J. For. Res. 15:66-71.

Location: North Carolina State University, Raleigh, North Carolina

Summary: This system is located in a greenhouse and intended to provide an inexpensive method of delivering regulated amounts of simulated rain solutions to seedlings grown in pots or flats. Depending on the glasshouse conditions, the system can accommodate either short- or long-term exposure studies. The only limitation might be the plant growing height and canopy size. Randomization of the flats or pots during exposure and growth is recommended. Given the stated objectives of the experimental design, the exposure system meets the needs of the study.

1. Hardware

a. Description

No data are reported for this particular application except for the 1.2-m height from bench to nozzle. Dimensions are flexible based upon surface area of bench space requiring rainfall application. The system consists of four independently-operated units.

b. Methodology

(1) Dispensing

Pressurized rainfall solutions are dispensed from two stainless steel cone nozzles per unit suspended 1.2 m above the bench. The system is manually activated.

(2) Chemical Analysis and Application Rate

The pH values of solutions prior to dispensing are measured. The application rate per plot is evaluated by collecting the deposition in 5 beakers placed on the soil surface. The application rate per plot is estimated by the mean of the 5 volumes. The chemistry of the incident rain is not reported.

(3) Protocol for Chemical/Temporal Exposure Dynamics

The chemistry of rainfall solutions is based on reported ionic concentrations in ambient rain (Cogbill and Likens, 1974) and is adjusted by additions of sulfuric and nitric acids to deionized water. The temporal exposure dynamics are prescheduled, providing 1.1 cm of rain in a 30-min event with a total of 36 events over a 16-week growing season.

c. Environment Controls

The exposure system is located in an environmentally controlled glasshouse providing regulated temperature, relative humidity, and photoperiod.

d. Data Acquisition

Not described.

2. Performance Evaluation

a. Wet Deposition Event

Calculated chemistry of the rainfall solutions. pH is measured in mixed solutions.

b. Wet Deposition Environment

Not described.

c. Non-Exposure Growth Environment

Not described.

d. Deposition Parameters

Soil deposition rate calculated but statistics are not reported. Deposition chemistry is calculated.

Diagram of system was not available.

Publication: Shriner, D. S., C. H. Abner, and L. K. Mann. 1977. Rainfall simulator for environmental application. Oak Ridge National Laboratory Technical Publication No. 5151. Oak Ridge National Laboratory, Oak Ridge Tennessee. 17 pp.

Additional Publications: Shriner, D. S., and J. W. Johnston. 1981. Effects of simulated, acidified rain on nodulation of leguminous plants by Rhizobium spp. Environ. Exp. Bot. 21:199-209.

Johnston, J. W., D. S. Shriner, C. I. Klarer, and D. M. Lodge. 1982. Effect of rain pH on senescence, growth, and yield of bush bean. Environ. Exp. Bot. 22:329-337.

Norby, R. J., and R. J. Luxmoore. 1983. Growth analysis of soybean exposed to simulated acid rain and gaseous air pollutants. New Phytol. 95:277-287.

Location: Oak Ridge National Laboratory, Oak Ridge, Tennessee

Summary: This rainfall simulator is situated in a controlled environment glasshouse and is designed to provide regulated rates of rainfall application to agricultural crops and forest tree seedlings grown in pots. The system consists of 12 nozzles per unit that inject rainfall solutions upward with deposition achieved by gravity. Distributional uniformity is achieved by a rotating platform. System performance has been characterized. The limitations of the systems are principally associated with growing and maintaining plants in a controlled-environment greenhouse.

1. Hardware

a. Description

The system is 3 m high, 1.25 m wide, and 2.1 m long. It is constructed of aluminum framing, while the platform is of wood construction. The platform, which has a surface area of 3.4 m^2 and is positioned 1.35 m below the rainfall nozzles, rotates at a rate of 2 rpm. The system consists of two independently-operated units.

b. Methodology

(1) Dispensing

Rainfall solutions are injected to the atmosphere by a series of mist and rain nozzles mounted along radial arms from a central hub. Droplets fall to the exposure table by gravity. Solutions are mixed using deionized water and analytical grade reagents. Dispensing is achieved either automatically by a programmable controller or by manual activation.

(2) Chemical Analysis and Application Rate

Routine chemical analysis consists of solution pH measured in both the stock solution and the deposited rain. More complete analysis of cations and anions is at the discretion of the researcher and commonly involves the deposited rain rather than the stock solution. Application rate is monitored by a volumetric cylinder fitted with a funnel and mounted at the same height as the canopy.

(3) Protocol for Chemical/Temporal Exposure Dynamics

Rainfall chemistry is based upon reported rainfall electrolytes (Shriner, 1979). The temporal aspects of the exposure are artificial and commonly selected to provide rates of application that simulate ambient conditions.

c. Environment Controls

The environmental conditions are those of the glasshouse environment which include charcoal filtration of air intake, steam heat, evaporative coolers, and photoperiod adjustment.

c. Data Acquisition

Not described.

2. Performance Evaluation

a. Wet Deposition Event

The coefficient of variation over time for rainfall chemistry is $\leq$ 50%. Droplet size has maximum coefficient of variation of 20%. Mean terminal velocity is 7.8 m s^{-1}. Distribution has a coefficient of variation of 4.0%. Exposure dynamics: intra-event time period is usually constant.

b. Wet Deposition Environment

Not described.

c. Non-Exposure Growth Environment

Only radiation and temperature reported. Charcoal-filtered air intake for glasshouse.

d. Deposition Parameter

Soil deposition rate coefficient of variation of $\leq$ 40%. Deposition chemistry coefficient of variation $\leq$ 50%.

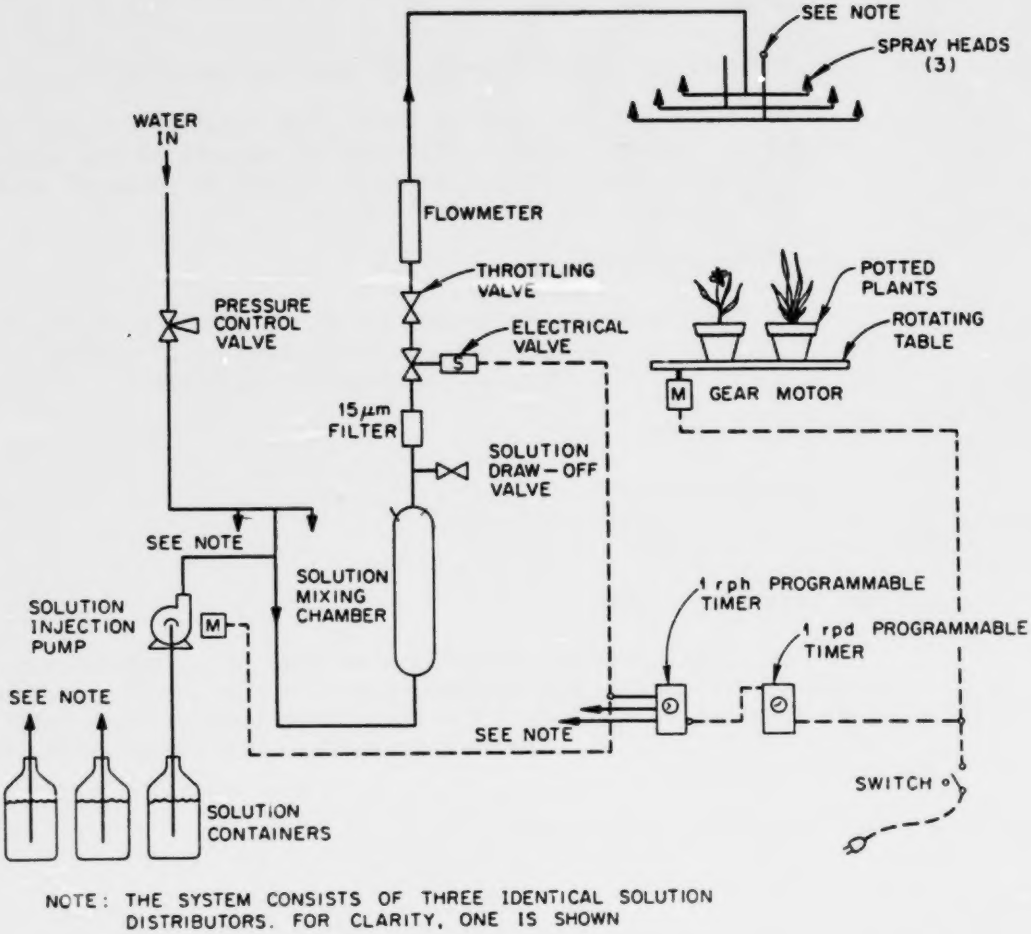


Figure F-2. Rain simulation system (reprinted from Shriner et al., 1977, Oak Ridge National Laboratory).

II. Outdoors

A. Non-Chambered Systems

Publication: Abrahamsen, G., K. Bjor, and O. Teigen. 1977. Field experiments with simulated acid rain in forest ecosystems. 1. Soil and vegetation characteristics, experimental design, and equipment. Research Report No. 4, 15 pp. 1432 NISK, Aas-NLH, Norway.

Additional Publications: Hagar, S., and B. R. Kjondal. 1981. Decomposition of birch leaves: dry weight loss, chemical changes, and effects of artificial acid rain. Pedobiologia 22:232-245.

Ogner, G., and O. Teigen. 1980. Effects of acid irrigation and liming on two clones of Norway spruce. Plant Soil 57:305-321.

Stuanes, A. O. 1984. A simple extraction as an indicator of soils' sensitivity to acid precipitation. Acta Agric. Scand. 34:113-127.

Location: Norwegian Forest Research Institute, Oslo, Norway

Summary: This system is designed for field application of simulated rainfall to an entire forest stand and has been used in a number of forest ecosystems in southern Norway. The objective of the multiple-year research project for which the system was devised is to characterize the influence of acidic wet deposition (i.e., sulfate addition) on tree growth, ground cover vegetation, and the chemical and biological dynamics of the soil system. The system applies simulated rain in excess of that which is deposited by natural events. Application is provided through a system of pipes supported by a boom that rotates around a central tower. The height of the tower can be adjusted to provide for variable canopy heights. The system is not capable of rainfall simulation during the winter so that all applications must be made during the May to September time period. Non-irrigated plots serve as controls for the effects of irrigation alone on ecosystem properties.

1. Hardware

a. Description

The system administers rain using a circular pivot irrigation system that services plots ranging in size from 15 m^2 to 625 m^2. The irrigation can be administered either above or below the canopy and, in the case of the latter, is provided by a system of pipes interspersed within the trunk space or on the forest floor.

b. Methodology

(1) Dispensing

Water is supplied to the forest through pipes lying on or above the ground or above the canopy. The pre-mixed rain simulant is fed through PVC pipes drilled at 0.1-m intervals and fitted with 0.1-m long capillary tubes to equalize pressure and maintain a constant delivery rate along the pipe's reach. The addition of sulfuric acid to the makeup water is automated to provide aliquots of concentrated sulfuric acid to a prescribed volume of water (e.g., 1:100).

(2) Chemical Analysis and Application Rate

Chemical analysis is done on incident ambient rain, incident rain simulants, throughfall, and stemflow using a variety of different collectors depending on the fraction required. The degree of variation in chemical constitution of the incident simulant is not reported as a function of time or residence time in the dispensing system. The methods for chemical anaysis are reported as being "standard methods" and are fully documented in various technical reports from the organization.

(3) Protocol for Chemical/Temporal Exposure Dynamics

The application protocol depends on the experimental design and is commonly done once a month, providing 25 to 50 mm rain per month with variable event duration (e.g., 20 min to 8 h), depending on plot size and system capacity. The chemistry of the rain simulant is commonly adjusted to provide increments in sulfur or nitrogen deposition to the system in excess of that delivered by ambient wet processes. Consequently, the simulant is adjusted solely for the sulfur and/or nitrogen content and pH.

c. Environment Controls

Typical ecological data are collected to provide climate and edaphic variables. With the exception of the hydrologic inputs, none of the variables is controlled.

d. Data Acquisition

Not described.

2. Performance Evaluation

a. Wet Deposition Event

Incident hydrometeor chemistry is reported.

b. Wet Deposition Environment

Not described.

c. Non-Exposure Growth Environment

Soil solution chemistry is described.

d. Deposition Parameter

Throughfall and stemflow chemistry is reported. Soil deposition rate, chemistry, and chemistry processing within the soil profile are reported.

Diagram of system was not available.

Publication: Irving, P. M., and J. E. Miller. 1981. Productivity of field-grown soybeans exposed to acid rain and sulfur dioxide alone and in combination. J. Environ. Qual. 10:473-478.

Location: Argonne National Laboratory, Argonne, Illinois

Summary: This system is designed to investigate the influence of rainfall chemistry on the growth and productivity of crop species under field conditions. It has the additional attribute of gaseous pollutant control so that the interactive effects of rainfall chemistry and gaseous air pollutants can be addressed through a zonal air pollution system of pipes interspersed above the canopy. The gaseous air pollutant feature provides for additions above ambient only rather than subambient. The system does not exclude ambient rain so that a companion plot is maintained with which to evaluate the influence of additional water input to the system.

1. Hardware

a. Description

A stainless steel spray head is suspended 2.4 m over each plot and supplied with simulant under positive pressure. Each spray head administers rain to one plot.

b. Methodology

(1) Dispensing

Simulant is dispensed through a stainless steel spray head. The degree of automation is not reported.

(2) Chemical Analysis and Application Rate

The chemistry of the deposited rain is measured for sulfate concentration using a barium sulfate precipitation method, while free acidity is measured with a pH electrode. Application rate is calculated, and adjusted to account for wind distribution.

(3) Protocol for Chemical/Temporal Exposure Dynamics

The chemistry of the rain simulant is selected based upon that occurring in ambient rainwater and includes multiple cations and anions. The measure of H^+ ion, sulfate, and nitrate deposition per plot takes into account the deposition via natural and simulated rainfall. The amount of rain simulant added is approximately 50% of the amount provided under ambient conditions. Simulated rainfall events are 20 min in duration providing 0.40 cm h^{-1}.

c. Environment Controls

None reported except for sulfur dioxide concentrations.

d. Data Acquisition

Not described for wet deposition component.

2. Performance Evaluation

a. Wet Deposition Event

Droplet size ranges from 0.6 to 3.3 mm diameter, with a median of 1.8 mm. Qualitative distribution statistics are reported.

b. Wet Deposition Environment

Ambient conditions.

c. Non-Exposure Growth Environment

Not described except SO_2 monitored and controlled.

d. Deposition Parameters

Soil deposition rate calculated.

Diagram of system was not available.

Publication: Shriner, D. S., C. H. Abner, and L. K. Mann. 1977. Rainfall simulation for environmental applications. Oak Ridge National Laboratory Technical Publication No. 5151. Oak Ridge, Tennessee. 17 pp.

Additional Publications: Heagle, A. S., R. B. Philbeck, P. F. Brewer, and R. E. Ferrel. 1983. Response of soybeans to simulated acid rain in the field. J. Environ. Qual. 12:538-543.

Brewer, P. F., and A. S. Heagle. 1983. Interaction between *Glomus geosporum* and exposure of soybeans to ozone or simulated acid rain in the field. Phytopathology 73:1035-1040.

Location: North Carolina State University, Raleigh, North Carolina; Oak Ridge National Laboratory, Oak Ridge, Tennessee

Summary: This system was designed in accordance with specifications developed at Oak Ridge but set up at Raleigh. The system is suitable for field use with low stature vegetation canopies and does not use an enclosure to exclude ambient rainfall. Consequently, all simulant additions are in excess of that delivered by ambient rain. The system does not control ambient levels of gaseous pollutants. The system dispenses rain from a single nozzle positioned at the end of a boom that pivots in a circle around a center post. Each plot is serviced by four booms.

1. Hardware

a. Description

Each boom has a radius of 0.9 m providing spray in a circular pattern. The maximum height of the boom is 1.5 m above the soil surface, although there is no structural reason that the height could not be extended to accommodate higher stature plant canopies. The minimum displacement between the height of the canopy and the boom in order to provide uniform distribution of the simulant is not recorded. Given the published dimensions of one unit (4 booms per unit), the effective spray area is 9.0 m^2. The field plot at N.C. State has 24 plots.

b. Methodology

(1) Dispensing

Rain simulant is dispensed under pressure to the calibrated, stainless steel rain nozzles that inject rain simulant upward. One system of a common rain chemistry services six field plots. The method and degree of automation are not reported.

(2) Chemical Analysis and Application Rate

On-site evaluation of simulant water chemistry is achieved through analysis of pH. More detailed analysis of simulant chemistry was done for three separate rain events in which the analysis was completed on deposited rain rather than the simulant in the dispensing system. The method of chemical analysis is not reported. The application rate of ambient rain is measured using two rainfall collectors located 30 m from the plot, while rainfall rates within plots are measured by six rain gauges. Reported data are means only. Nozzles with delivery rates that vary by more than 10% of the mean rate of 0.63 m min^{-1} at 400 Pa pressure for 30 s were rejected.

(3) Protocol for Chemical/Temporal Exposure Dynamics

Rainfall chemistry is based upon rainwater data for ambient conditions (Cogbill and Likens, 1974) with pH adjustment achieved through the addition of sulfuric and nitric acids. The simulant provides multiple cations and anions. The temporal exposure dynamics are artificial in that all simulants are added between 0600 and 0800 h for a total of 30 min (rain delivered in three 10-min intermittent showers). The frequency of events and the duration of inter-event periods are not reported.

c. Environment Controls

Not described.

d. Data Acquisition

Not described.

2. Performance Evaluation

a. Wet Deposition Event

Mean droplet size is 0.9 mm. Mean terminal velocity is 7.8 m s^{-1}. There is little variation in distribution between rain events, but there is a marked edge effect for each plot.

b. Wet Deposition Environment

Exposure is under ambient conditions.

c. Non-Exposure Growth Environment

Soil solution chemistry is reported.

d. Deposition Parameters

Not described except for chemical processing in soil profile.

B. Chambered Systems

Publication: Irving, P. M. W. Prepejchal, and J. E. Miller. Experimental facility for long-term studies of acidic deposition effects on plant/soil systems. Personal communication.

Additional Publication: Irving, P. M. 1985. Biochemical transformations in two plant/soil systems exposed to simulated acidic precipitation. In: Proceedings of the Seventh International Symposium on Environmental Biogeochemistry, Rome, Italy.

Location: Argonne National Laboratory, Chicago, Illinois

Summary: This facility is identified as the Microcosm for Acid Rain Studies (MARS). It consists of a steel framework 57 m long and 9 m wide, supporting a polyethylene roof. The maximum height of the roof is 5 m; the distance between the nozzles and soil surface is 2.44 m. The enclosure cannot be operated during winter. Within the 516 m^2 of surface area under the enclosure, rectangular microcosms (2.4 x 1.2 x 1.4 m) are used to study plant/soil responses to acidic precipitation. The microcosms are equipped with ceramic soil-water samplers positioned at various depths in each microcosm.

1. Hardware

a. Description

See above.

b. Methodology

(1) Dispensing

Rainfall is generated by stainless steel nozzles positioned 2.44 m above the soil surface. The nozzles produce a square deposition pattern with uniform distribution. The source water is deionized just prior to the rain event. Simulant chemistry is based on reported data from the Midwest and includes multiple cations and anions, with pH adjustment achieved with sulfuric and nitric acids. The mode of mixing is in-line rather than batch and is achieved using fluid metering pumps.

(2) Chemical Analysis and Application Rate

Method for characterizing deposition is inferential. Conductivity of the solutions are monitored and recorded. Methods for chemical analysis are not reported.

(3) Protocol for Chemical/Temporal Exposure Dynamics

Rainfall chemistry is based on reported data from NADP from the Midwest region. The rainfall deposition rate is fixed at 0.06 cm min^{-1}, and a controller is used to lengthen the "on" and "off" periods to achieve the desired rain event duration. The physical features of rain events are selected to simulate ambient conditions (i.e., events/week, cm/event).

c. Environment Controls

Not described.

d. Data Acquisition

Capabilities for acquisition are mentioned but not described.

2. Performance Evaluation

a. Wet Deposition Event

Chemical data are not reported.

b. Wet Deposition Environment

Data are not reported.

c. Non-Exposure Growth Environment

Data are not reported.

d. Deposition Parameters

Soil deposition rates of the hydrometer are constant across treatments. The chemical concentration of cations and anions vary among microcosms.

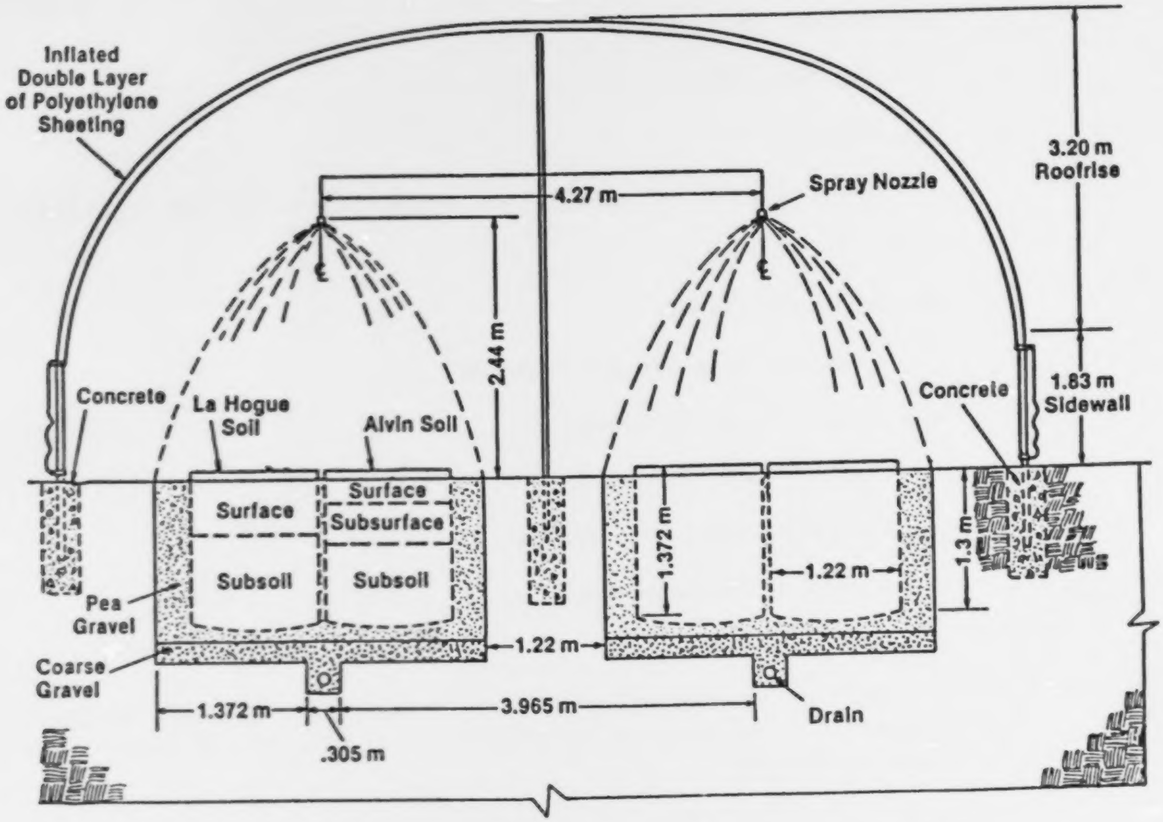
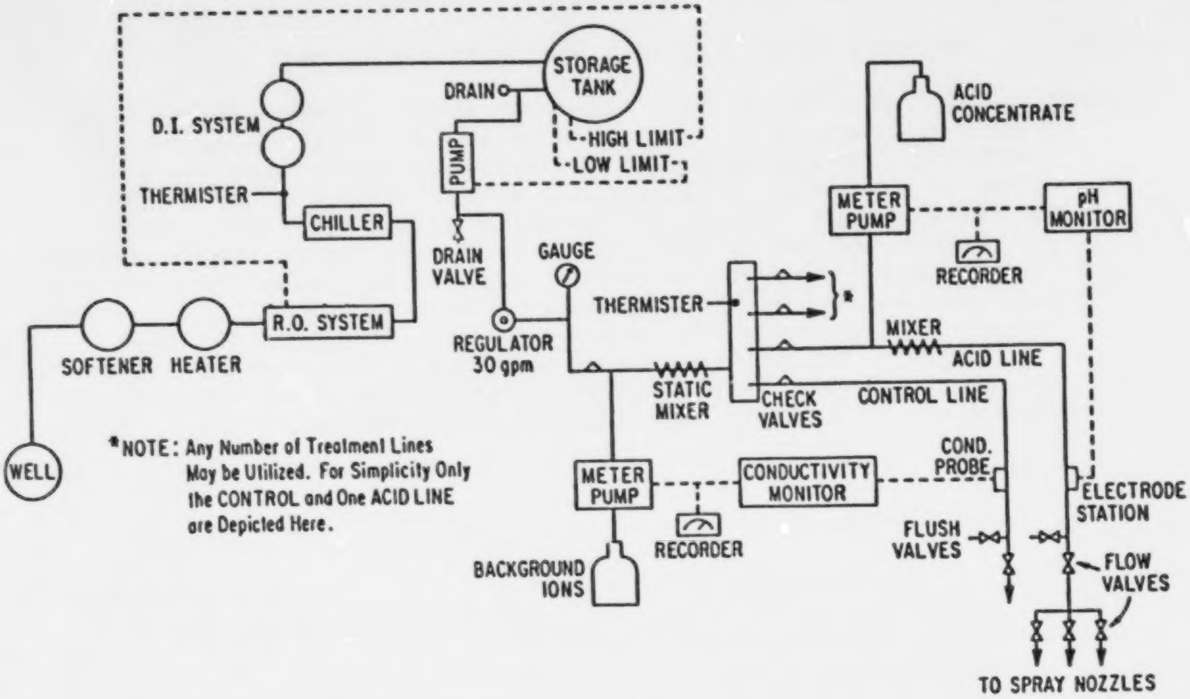


Figure F-3. Cross-section of microcosm facility with rainfall simulation over two pairs of plots (P. M. Irving, personal communication).



*NOTE: Any Number of Treatment Lines May be Utilized. For Simplicity Only the CONTROL and One ACID LINE are Depicted Here.

Figure F-4. Rain simulant metering and pumping system with feedback control (P. M. Irving, personal communication).

Publication: Kelly, J. M., R. C. Strickland, F. P. Weatherford, and J. C. Noggle. 1984. Evaluation of simulated acid precipitation effects on forest microcosm. Final Report to the Electric Power Research Institute, RP-1632. EPRI EA-3500. Electric Power Research Institute, Palo Alto, California.

Additional Publication: Kelly, J. M., and R. C. Strickland. 1984. CO_2 efflux from deciduous forest litter and soil in response to simulated acid rain treatment. Water, Air, Soil Pollut. 23:431-440.

Location: Tennessee Valley Authority, Muscle Shoals, Alabama

Summary: This system was used for a 30-month period to expose forest microcosms to simulated acidic precipitation in a manner approximating field conditions. The microcosms are sheltered from ambient rain via a rain-activated lid system. Simulated rain is administered at the discretion of the research staff. During periods of artificial rain, the plots are sheltered on the top and sides to reduce ambient radiant energy, and the rate of rainfall addition per week is adjusted to provide the plots with the equivalent of the 30-year average per week for the region. Microcosm analyses include vegetation (tree seedlings), soils, soil solution (lysimeters), root growth, and leaf physiology. Treatments are maintained throughout the year. The uniqueness of the system is its focus on integrating responses of the vegetation and soil components.

1. Hardware

a. Description

Each microcosm is 1.2 by 1.2 by 1.0 m. The depth measurement is solely for the soil component. The aboveground height for the vegetation component is limited by the shelter lid and is $\leq$ 1.5 m, although none of the seedlings reached that height. The system consists of five separate units, four microcosms per unit. The soil component is sealed on the sides and bottom and fitted with a lysimeter at the bottom for monitoring soil solution chemistry.

b. Methodology

(1) Dispensing

Dispensing is not automated for unattended operation. Manual activation of the pumping system provides delivery of rainfall simulants to each microcosm. The shelter-lid system is automated for closure by a rain-activated sensor. The method of dispensing is by calibrated spray nozzles mounted in each unit on the shelter lid.

(2) Chemical Analysis and Application Rate

The methodology for chemical analysis of incident precipitation is not described; throughfall chemistry is well characterized for cations, anions, conductivity, and total nitrogen. The rate of throughfall is measured in each microcosm by four collection vessels.

(3) Protocol for Chemical/Temporal Exposure Dynamics

The chemistry of the rainfall simulants is based on ambient rainfall chemistry and includes a balance of cations and anions with pH adjustment via sulfuric and nitric acid additions. The feed water originates from a tap and is then deionized. The pH of each rainfall event is programmed to change (i.e., increase) over the event period in a manner similar to that which occurs during ambient rainfall events. The temporal exposure dynamics are pre-scheduled to be one event per week with the duration of the exposure selected to deliver rain in an amount equal to the 30-year average for that time of the year.

c. Environment Controls

No continuous monitoring or control of aboveground environmental conditions is intended. Soil solution chemistry is monitored on a regular basis.

d. Data Acquisition

Not described.

2. Performance Evaluation

a. Wet Deposition Event

Chemistry of stock solutions is recorded. Coefficient of variation for rainfall distribution is $\leq$ 20%.

b. Wet Deposition Environment

Not described.

c. Non-Exposure Growth Environment

Ambient conditions. Coefficient of variation for soil solution chemistry is $\leq$ 50%.

d. Deposition Parameters

Coefficient of variation for throughfall chemistry is $\leq$ 30%. Coefficients of variation for soil deposition rate, chemistry, and profile processing are $\leq$ 30%.

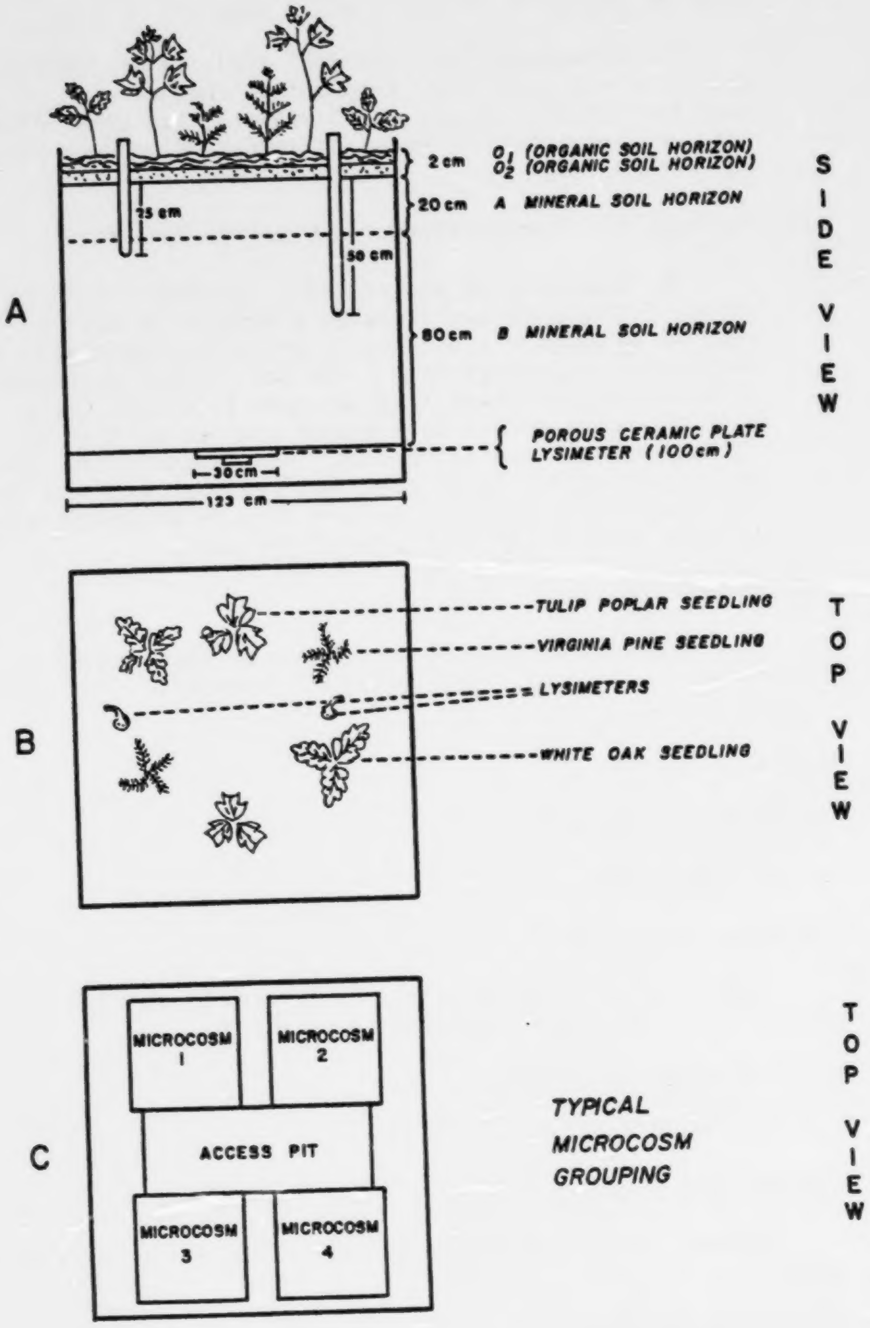


Figure F-5. Schematic drawing of the features of an individual microcosm as well as the arrangement of microcosms within a shelter (reprinted from Kelly *et al.*, 1984, Electric Power Research Institute).

Publication: Lee, J. J., G. E. Neely, S. C. Perrigan, and L. C. Grothaus. 1981. Effect of simulated sulfuric acid rain on yield, growth, and foliar injury of several crops. Environ. Exp. Bot. 21:171-185.

Additional Publication: Lee, J. J., and D. E. Weber. 1979. The effect of simulated acid rain on seedling emergence and growth of eleven woody species. Forest Sci. 25:393-398.

Location: U.S. Environmental Protection Agency, Corvallis, Oregon

Summary: This field facility consists of three different types of chambers from which ambient rain is excluded by a permanently-mounted transparent plastic cover. The sides of the chambers are open for forced air ventilation which is provided by plenum boxes. Because plants are grown in pots, the facility can accommodate both agricultural crops and forest tree seedlings. The selection of species is restricted to those species and cultivars that grow well in the Willamette Valley. The plenum boxes were not equipped with charcoal filters so that ambient gaseous pollutant levels were experienced in all chambers.

1. Hardware

a. Description

Three different chamber designs are utilized. The four large round chambers are 4.6 m in diameter by 2.4 m high providing a 16.6 m^2 surface area for plots. The 20 square chambers are 2.4 m wide and 2.1 m in height, providing a 5.8 m^2 surface area. The eight small round chambers are 3.0 m in diameter and 2.4 m high, providing a surface area of 7.1 m^2. The only source of turbulence for the chambers is the forced air system.

b. Methodology

(1) Dispensing

The source of water for rainfall solutions is that provided for routine irrigation, which is subsequently deionized. Simulant chemistry is based on published data for rainfall in the northeastern United States, and acidity is adjusted by addition of sulfuric and nitric acids. The temporal exposure dynamics are fixed at three equal duration events per week. The time of day for exposure is not specified. The method of dispensing is through a stainless steel nozzle.

(2) Chemical Analysis and Application Rate

The chemistry is provided for the irrigation water but not for rain solutions either in storage or after dispensing in the system. The number of equivalents of assorted cations and anions per liter added to the irrigation water is repeated. The method of measuring application rate is not repeated.

(3) Protocol for Chemical/Temporal Exposure Dynamics

Rainfall chemistry is based upon 7-year average as described above. Temporal exposure simulates the intermittent nature of the rainfall events relative to intervening periods of dry deposition but the dynamics of exposure are pre-scheduled. The rate of application is 30 mm wk^{-1} provided in three separate events of equal duration.

c. Environment Controls

Information is provided on ambient pollutant levels for SO_2 and O_3. Pollutant levels are not controlled. The development of visible foliar symptoms of injury is monitored.

d. Data Acquisition

Not described.

2. Performance Evaluation

a. Wet Deposition Event

Chemistry data are available for irrigation water only.

b. Wet Deposition Environment

Not described.

c. Non-Exposure Growth Environment

Air turnover rate is reported except for large chambers. Trace pollutant levels and soil solution chemistry are reported.

d. Deposition Parameters

Soil deposition rate is reported.

Diagram of the system was not available.

Publication: Troiano, J., L. Colavito, L. Heller, D. C. McCune, and J. S. Jacobson. 1983. Effects of acidity of simulated rain and its joint action with ambient ozone on measures of biomass and yield in soybean. Environ. Exp. Bot. 23:113-119.

Additional Publications: Troiano, J., L. Colavito, L. Heller, and D. C. McCune. 1982. Viability, vigor, and maturity of seed harvested from two soybean cultivars exposed to simulated acidic rain and photochemical oxidants. Agric. Environ. 7:275-283.

Troiano, J., L. Heller, and J. S. Jacobson. 1982. Effect of added water and acidity of simulated rain on growth of field-grown radish. Environ. Pollut. (Ser. A) 29:1-11.

Location: Boyce Thompson Institute, Ithaca, New York

Summary: This facility consists of a traditional open-top chamber modified with a loosely-fit clear tarpaulin hood to exclude ambient rainfall but not restrict the normal exchange rate of ambient or charcoal-filtered air. Temperature and irradiance are affected by the tarpaulin and the degree of change in each factor is reported. Rainfall solutions are delivered to each chamber via a single nozzle mounted in the center of the plot. The facility is suited for evaluating the potential for interaction between rainfall acidity and elevated levels of gaseous pollutants (e.g., ozone).

1. Hardware

a. Description

Each chamber is a traditional open-top 2.44 m in diameter and 2.44 m high. The surface area for growing plants inside the chambers is 4.7 m^2 and the maximum height for plant growth is 2.44 m. The nozzle dispenses rain only over a 3.14 m^2 area so that the border plants cannot be sampled.

b. Methodology

(1) Dispensing

The solution is under positive pressure to the raindrop nozzles which are upward-facing. The degree of automation for the dispensing is not reported.

(2) Chemical Analysis and Application Rate

The methodologies for chemical solution analysis and evaluation of application rate within the chamber are not reported.

(3) Protocol for Chemical/Temporal Exposure Dynamics

The chemistry of the rainfall simulant is adjusted to different pH levels using sulfuric and nitric acids added to deionized water. The levels of ammonium, chloride, and calcium are constant among the treatments. The temporal dynamics are adjusted to provide rainfall events in the early evening or on cloudy days. The individual rainfall events were typically of 1 hr duration, providing 1.3 cm h^{-1} of rain.

c. Environment Controls

The environment inside the chamber is reported to be only slightly modified with respect to that of normal open-top chambers. The most marked changes are in air temperatures (< 3°C) and irradiance (attenuated 25%). The ozone levels are monitored and controlled to be either ambient or some percentage of ambient (5% or 60%).

d. Data Acquisition

Not described.

2. Performance Evaluation

a. Wet Deposition Event

None reported.

b. Wet Deposition Environment

Light is attenuated 25%. Maximum temperature increase is 3°C. Wind and turbulence are maintained during treatments.

c. Non-Exposure Growth Environment

Trace pollutant levels are well characterized.

d. Deposition Parameters

Mean deposition rate to soil is 1 cm h^{-1}.

C. Automated Exclusion Systems with Scheduled Rainfall Addition

Publication: Johnston, J. W., D. S. Shriner, and C. H. Abner. 1986. Design and performance of an exposure system for measuring the response of crops to acid rain and gaseous pollutants in the field. J. Air Pollut. Control Assoc. 36:894-899.

Additional Publications: Norby, R. J., B. K. Takemoto, J. W. Johnston, and D. S. Shriner. Acetylene reduction rate as a physiological indicator of the response of field-grown soybeans to simulated acid rain and ambient gaseous pollutants. Environ. Exper. Bot. (in press).

Takemoto, B. K., D. S. Shriner, and J. W. Johnston. Effects of simulated acid rain and gaseous air pollutants on the physiological responses of field-grown soybean. Personal communication.

Location: Oak Ridge National Laboratory, Oak Ridge, Tennessee

Summary: This system is designed to provide control of both wet and dry deposition under field conditions and is suitable for both agricultural species and forest tree seedlings. Open-top chambers are used in conjunction with an automated system for rain exclusion and addition with exclusion being achieved by covers activated by a Wong rain sensor. The system's current configuration can accommodate three different rainfall chemistry treatments in addition to that of ambient rain. The ability to automatically dispense simulated rain during, and in the amounts equal to, natural rain events is unique to this system.

1. Hardware

a. Description

The open-top chambers are the original design, i.e., an aluminum frame 3.05 m in diameter and 2.44 m high and wrapped in two side panels of polyvinyl chloride plastic film. The lower panel is double-walled and perforated on the inner wall with 2.5-cm diameter holes. The air flow rate through the chamber is approximately 70 m^3 min^{-1}, providing four complete air exchanges per minute. The exclusion lids are 4.27 m^2 fiberglass sheets mounted on a tract system 2.7 m above the ground. The exclusion lids do not cap the chambers so that air flow through the chamber is maintained during a rain event. The growing area dimensions are a cylinder of 7.3 m^2 (basal area) and < 2 m (height). The system consists of 36 independently operated units set out in 4 rows. The system is equipped for ozone monitoring and addition using an IBM personal computer and a site-specific software package.

b. Methodology

(1) Dispensing

Well water is sand- and charcoal-filtered and deionized. Analytical grade reagents are mixed in a batch mode and stored for periods of <2 weeks. Solutions of prescribed chemistry are delivered under positive pressure to wide-angle, full cone spray nozzles mounted on the underside of each exclusion lid (one per lid or chamber). The mixing is done manually while the dispensing is automated, directed by the minicomputer that logs the rate of rainfall in an ambient plot.

(2) Chemical Analysis and Application Rate

The performance criteria for simulation were achieved using beakers placed at ground level in each of the chambers. On-site chemical analysis is restricted to pH measurements, while more detailed characterization is achieved using ICP and AA. On-site application rate is monitored by a bucket rain gauge in one ambient and one simulated rainfall plot.

(3) Protocol for Chemical/Temporal Exposure Dynamics

The chemistry is based upon reported mean rainfall chemistry for the growing season including multiple cations and anions. The pH adjustment is made through sulfuric and nitric acid additions. Rainfall rates in an ambient plot and one simulant plot are monitored using tipping bucket rain gauges for which the data are logged.

c. Environment Controls

Environmental conditions (edaphic, climatic, and atmospheric) are monitored and logged. The only control is for wet and dry deposition.

d. Data Acquisition

Continuous monitoring and data logging are conducted for rainfall rates, ozone concentration, air temperature, wind speed, irradiance, soil water potential, and SO_2 concentration. The duration of individual rainfall events is also logged.

2. Performance Evaluation

a. Wet Deposition Event

Chemistry of incident precipitation is reported. Distribution of rainfall among chambers is characterized qualitatively.

b. Wet Deposition Environment

Not described.

c. Non-Exposure Growth Environment

Ambient conditions are reported but no dispersion statistics available except for ozone.

d. Deposition Parameters

Data for rainfall deposition rates and cumulative sulfur and nitrogen are reported.

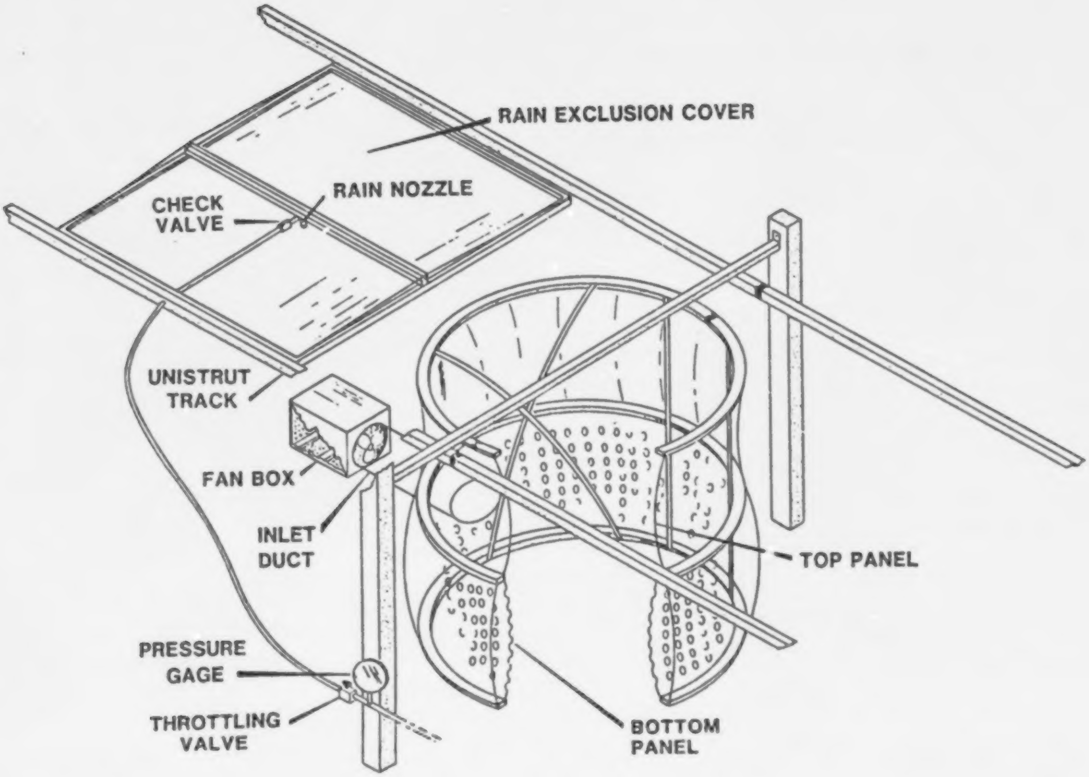


Figure F-6. Detail of an open-top chamber, rain exclusion cover, and simulant dispensing apparatus (reprinted from Johnston et al., 1986, with permission of the Air Pollution Control Association).

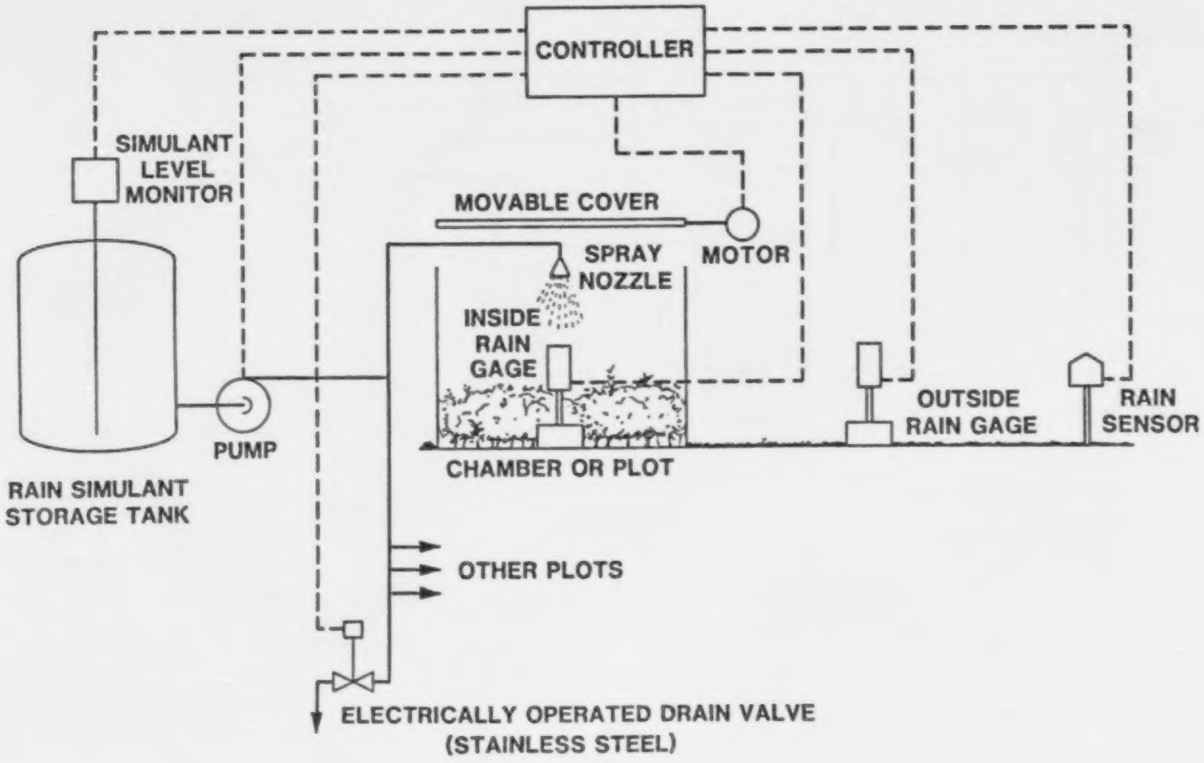


Figure F-7. Schematic illustrating the automatic control circuitry (reprinted from Johnston et al., 1986, with permission of the Air Pollution Control Association).

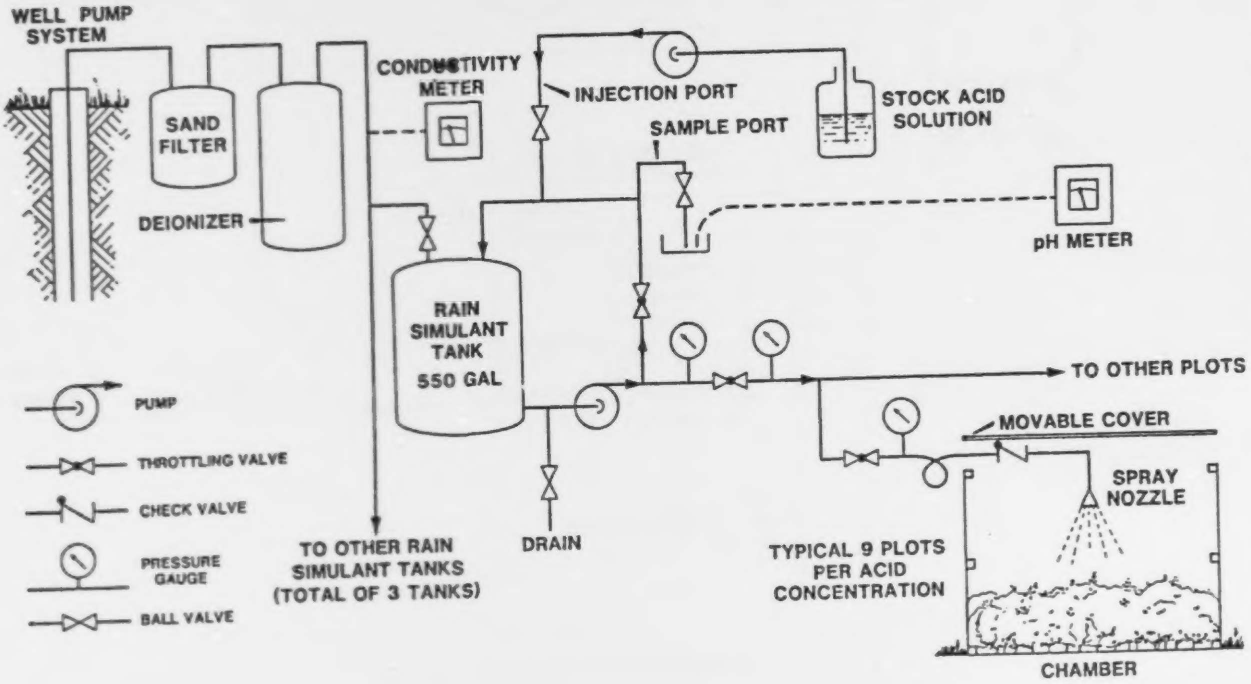


Figure F-8. Schematic illustrating pipe connections for the water purification, simulant mixing, and simulant dispensing systems (reprinted from Johnston *et al.*, 1986, with permission of the Air Pollution Control Association).

Publication: Kuja, A., R. Jones, and A. Enyedi. 1986. A mobile rain exclusion canopy and gaseous pollutant reduction system to determine dose-response relationships between simulated acid precipitation and yield of field grown crops. Air, Water, and Soil Pollution 31:307-315.

See description in Appendix D.

Publication: Lewin, K. F., and L. S. Evans. 1984. Design of an experimental system to determine the effects of rainfall acidity on vegetation. Brookhaven National Laboratory Report No. 34649. Upton, New York. 15 pp.

Additional Publications: Evans, L. S., K. F. Lewin, M. J. Patti, and E. A. Cunningham. 1983b. Productivity of field-grown soybeans exposed to simulated acidic rain. New Phytol. 93:377-388.

Banwart, W. L. 1985. Quality assurance plan for: Simulated acid rain effects on yield and growth of corn and soybeans and on soil parameters. Department of Agronomy, University of Illinois, Urbana, Illinois. 14 pp.

Location: Brookhaven National Laboratory, Upton, New York. This shelter design is replicated at the University of Illinois (4 units) and Pennsylvania State University.

Summary: The principal component of this system is the rainfall exclusion shelter capable of covering vegetation canopies within 50 to 60 s after being activated by an electronc rain sensor. The rain distribution system is attached to the shelter's infrastructure and dispensing usually is done at night (1800 to 2400 h) or on cloudy days. The shelter is a commercially-purchased greenhouse constructed of steel channels covered with polyethylene sheets. The frame is modified to rest on a track/rail system. Because the plants are exposed to ambient conditions except during the ambient or simulated rainfall events, the system is suitable for long-term studies under standard agronomic or forest practices. Given the shelter's height and area dimensions, it is well suited for studies of both agricultural crops and forest tree seedlings/saplings grown either in pots or in the ground. The size of the facility also lends itself to plot/subplot replication within a single shelter unit.

1. Hardware

a. Description

Each shelter is approximately 10 m wide, 30 m long, and 4.3 m high above the soil. The openings at each end are partially covered with plastic to limit incursion of wind-blown rain and mist. The plant growing area is approximately 300 m^2 while the maximum height would depend on the vertical distribution of rainfall under each shelter. The maximum height is not likely to exceed 3.5 m. This shelter system is replicated twice at Brookhaven.

b. Methodology

(1) Dispensing

The exclusion shelter is automatically activated, while the dispensing is manually initiated. Nozzles are mounted on the shelter structure, and their specifications vary as a function of the desired spray pattern and plot size. Premixed rain solutions (either mixed in-line or as a batch and stored) are delivered to the nozzles under pressure. The mixing of in-line rainfall solutions is automated via a programmable pH controller.

(2) Chemical Analysis and Application Rate

The method for analyzing the simulated rainfall chemistry is not specified. Reported chemistries are for in-line solution and calculated with recipes. The temporal dynamics and chemistry of ambient rain are reported. The method for measuring rainfall distribution/application rate within the shelter, either on a routine basis or as a means of evaluating the distributional performance of nozzles, is not reported although deposition rates are provided in manuscripts.

(3) Protocol for Chemical/Temporal Exposure Dynamics

The chemistry of rainfall solutions is based upon reported ambient mean rainfall chemistry in the northeastern United States and includes major cations, major anions, and multiple trace elements. The makeup water is deionized prior to mixing of the solutions, and the pH of the solution is adjusted with additions of sulfuric and nitric acids. The temporal features of rainfall additions are pre-scheduled and usually administered at night or on cloudy days to avoid temperature effects in the shelter. The rate of application is set to simulate realistic rates of application on a weekly basis as determined from 24 years of consecutive records in the region.

c. Environment Controls

Local gaseous air pollutants are evaluated on a weekly basis. The shelters are not equipped to exclude ambient levels of gaseous pollutants. The vegetation canopy experiences ambient conditions except during natural or simulated rainfall events.

d. Data Acquisition

Air quality data under ambient conditions (rainfall and dry deposition) are commonly logged. No other forms of data acquisition are reported.

2. Performance Evaluation

a. Wet Deposition Event

Chemistry is calculated from solution mix.

b. Wet Deposition Environment

Not described.

c. Non-Exposure Growth Environment

Not applicable.

d. Deposition Parameters

Soil deposition rate is calculated.

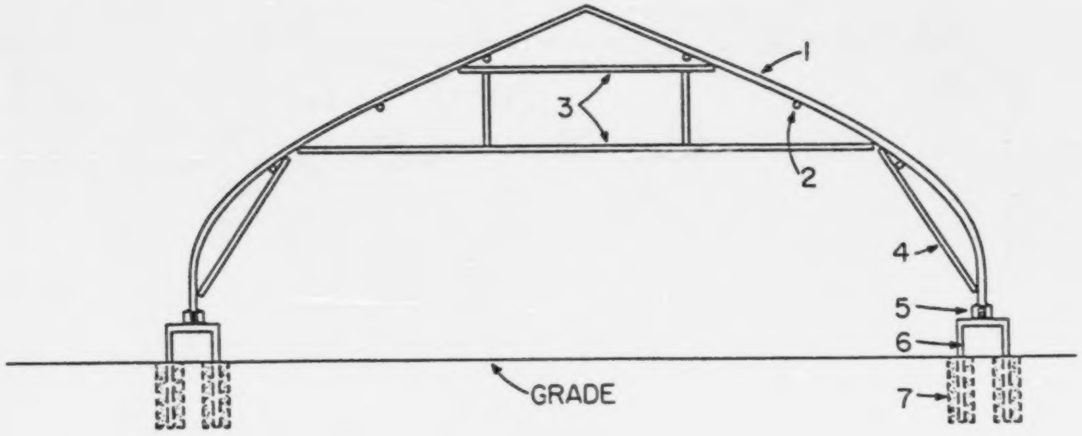


Figure F-9. Cross-section view of wet deposition system shelter at a wheel assembly showing major structural components. (1) Rafter bow; (2) purlin; (3) horizontal bracing; (4) knee bracing; (5) wheel assembly; (6) track supports; (7) concrete foundation (reprinted from Lewin and Evans, 1984, Brookhaven National Laboratory).

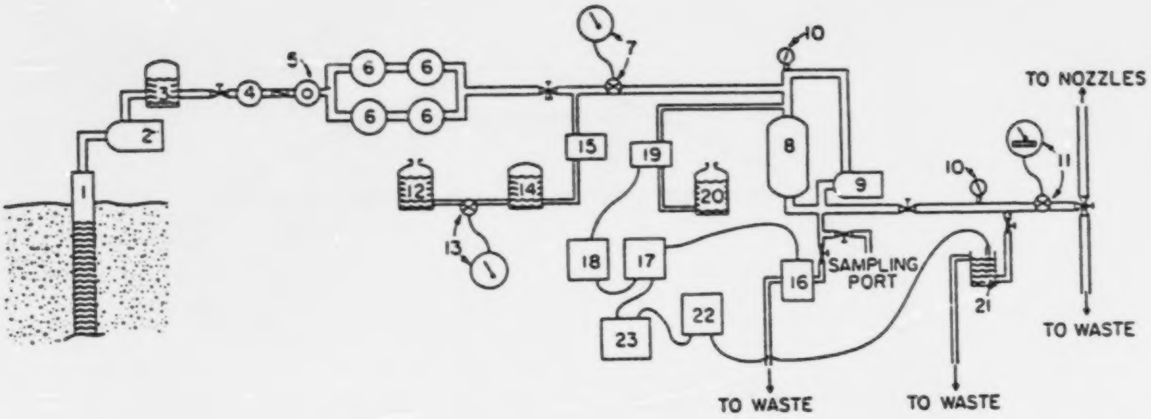


Figure F-10. Schematic of in-line simulated rain mixing system in use at Brookhaven National Laboratory: (1) well; (2) well pump; (3) pressurized storage tank; (4) 5-micron filter; (5) flow controller; (6) mixed-bed deionizing units; (7) electronic flow sensor; (8) mixing tank; (9) recirculating pump; (1) pressure gauges; (11) electronic flow sensor/accumulator; (12) simulated rain concentrate storage tank; (13) electronic micro-flow sensor; (14) pulse dampener; (15) adjustable, positive displacement metering pump; (16) electrode station for pH monitor/controller; (17) pH monitor/controller assembly; (18) electronic motor speed controller; (19) electronically adjusted positive displacement metering pump; (20) acid storage carboy; (21) laboratory grade pH probe and automatic temperature compensator; (22) pH monitor for quality conrol; (23) two-pen chart recorder for pH (Lewin and Evans, 1984, Brookhaven National Laboratory).

APPENDIX G

Descriptions of Facilities and Performance Evaluations -- Systems for Aerosol/Mist Simulation Research

I. INDOORS

Publication: Gmur, N. F., L. S. Evans, and K. E. Lewin. 1983a. Effects of ammonium sulfate aerosols on vegetation. I. Chamber design for long duration exposures. Atmos. Environ. 17:707-714.

Additional Publication: Gmur, N. F., L. S. Evans, and K. F. Lewin. 1983b. Effects of ammonium sulfate aerosols on vegetation. II. Mode of entry and responses of vegetation. Atmos. Environ. 17:715-721.

Location: Brookhaven National Laboratory, Upton, New York

Summary: A plant growth chamber has been constructed to expose a large number of plants to a uniformly distributed concentration of submicrometer aerosols of known particle size distribution and chemistry for periods of up to 3 weeks. The chamber design, with features controlled externally, provides regulation of wind velocity, temperature, relative humidity, air exchange, lighting, irrigation, and aerosol injection. This facility provides adequate plant growth in the presence and absence of submicrometer ammonium sulfate aerosols in order to determine deposition rates, mode of entry, and effects of submicrometer aerosols on vegetation.

1. Hardware

a. Description

The unit is 6 m long, 3 m wide, and 2.2 m high. The plant growing area is a 2.1 m^2 area turntable. Root zone manipulation and studies in combination with other forms of wet and dry deposition are possible.

b. Methodology

(1) Dispensing

Solution is atomized into a duct; the duration of atomization is programmable.

(2) Chemical Analysis and Application Rate

Rate of deposition is characterized by elution of aerosol from leaves and chemical analysis of eluted ammonia via electrode. Aerosols in the atmosphere are collected via filter sample for subsequent ammonium sulfate determination with specific ion electrode.

(3) Protocol for Chemical/Temporal Exposure Dynamics

Chemistry is based on reported atmospheric concentrations of ammonium sulfate.

c. Environment Controls

Air is filtered and conditioned for temperature, relative humidity, and aerosol concentration. Water is deionized.

d. Data Acquisition

Temperature, light, and duration of event are recorded.

2. Performance Evaluation

a. Wet Deposition Event

Distribution of aerosol sizes is well characterized spatially and temporally. Distribution uniformity is based on a turntable approach.

b. Wet Deposition Environment

Wind speed mean 0.25 m s^{-1}.

c. Non-Exposure Growth Environment

Same as for (b).

d. Deposition Parameters

Foliar interception and retention of aerosols on leaves is recorded; mean deposition velocity is 3.2×10^{-3} cm s^{-1}.

Diagram of system not available.

Publication: McCune, D. C., D. H. Silberman, R. H. Mandl, L. H. Weinstein, P. C. Freudenthal, and P. A. Giardina. 1977. Studies on the effects of saline aerosols of cooling tower origin on plants. J. Air Pollut. Control Assoc. 27:319-324.

Additional Publication: Silberman, D. H., and D. C. McCune. 1978. Some factors affecting the response of plants to simulated cooling tower saline mist. In: Proceedings of a Symposium on Environmental Effects of Cooling Tower Emissions. WRRC Special Report No. 9, University of Maryland. pp. 1-9.

Location: Boyce Thompson Institute for Plant Research, Ithaca, New York

Summary: This aerosol facility consists of three exposure systems located in a remodeled glasshouse. The glasshouse is equipped to provide physical protection for the aerosol chambers, buffer the environmental control systems of the chambers, and provide a temporary holding area for the plants before and after the exposure. The system is well characterized with respect to the rate of deposition, atmospheric concentration, and particle size distribution.

1. Hardware

a. Description

Each chamber consists of a 13.3 m^3 enclosure formed by a footing upon which a wood frame and aluminum channel are covered with Mylar sheeting. The plastic dome is Quonset-shaped; air is discharged from a tubular plenum positioned at the arc. Each chamber is equipped with a turntable. Air flowing into the chamber from the plenum is drawn out through a metal grilled floor.

b. Methodology

(1) Dispensing

The principal method for particle generation in each chamber is atomization by a pneumatic nozzle. Larger particles are generated with hydraulic nozzles and suspended saline particles are generated using pneumatic nozzles.

(2) Chemical Analysis and Application Rate

Deposition rate is estimated using parafilm positioned on the edge of the turntable. Collected particles are eluted and the saline content determined. Atmospheric concentration of saline particles are estimated following collection on a filter membrane sampling air at a fixed rate. Particle size distribution is estimated using a rotating drum impactor followed by a filter membrane. Larger particles are collected on glass slides coated with magnesium oxide.

(3) Protocol for Chemical/Temporal Exposure Dynamics

A range of exposure dynamics was employed to provide dose-response relationships for a variety of species.

c. Environment Controls

Air was conditioned to 27.5°C and 85% relative humidity. Supplementary lighting was provided by two Sunbrella light fixtures per chamber.

d. Data Acquisition

Methods for data acquisition are not described.

2. Performance Evaluation

a. Wet Deposition Event

Data regarding distributional uniformity are not described, although plants were maintained on a rotating platform.

b. Wet Deposition Environment

See 2a.

c. Non-Exposure Growth Environment

Design utilized controlled environments before and after exposure to minimize growth differences due to microclimatic variation. Data are not reported.

d. Deposition Parameters

Coefficient of variation for foliar deposition was less than or equal to 50%, with most of the values being less than 20%.

Diagram of the system is not available.

Publication: Musselman, R. C., J. L. Sterrett, and A. L. Granett. 1985. A portable fogging apparatus for field or greenhouse use. HortScience 20:1127-1129.

Location: Statewide Air Pollution Research Center, Riverside, California

Summary: This is a portable fogging system for use in growth chambers, glasshouses, or field environments to deliver a chemically defined solution to plant surfaces. The fogger consists of a solution cannister, fog nozzle, and compressed air, and a frame enclosure covered with polyethylene film to contain the fog. The system description provides engineering specifications only (i.e., no biological characterization).

1. Hardware

a. Description

Enclosure size is variable with typical size being 3.3 x 3.3 x 3.3 m. Plant growing area is variable. The number of units is unlimited.

b. Methodology

(1) Dispensing

Pressurized solution is impinged on a pin to disassociate solution into fog-sized particles. Dispensing can be activated by a timer.

(2) Chemical Analysis and Application Rate

Not described.

(3) Protocol for Chemical/Temporal Exposure Dynamics

Chemistry is subject to the discretion of the research objective. Fogging is most effective during night-time exposures.

c. Environment Controls

The enclosure will significantly modify the atmosphere. Daytime exposures are not recommended.

c. Data Acquisition

Not described.

2. Performance Evaluation

a. Wet Deposition Event

Data on droplet size available from nozzle manufacturer only.

b. Wet Deposition Environment

No wind speed possible.

c. Non-Exposure Growth Environment

Not described.

d. Deposition Parameters

Not described.

Diagram of system is not available.

Publication: Scherbatskoy, T., and R. M. Klein. 1983. Response of spruce and birch foliage to leaching by acidic mists. J. Environ. Qual. 12:189-195.

Location: University of Vermont, Burlington, Vermont

Summary: This system consists of indoor, polyethylene-lined chambers in which mist droplets are generated. The enclosure provides a suitable environment for evaluating the potential for acidified mists to leach multiple cations and anions from foliage. The system is not designed to accommodate long-term exposures to mist.

1. Hardware

   a. Description

      No specifications or design features reported.

   b. Methodology

      (1) Dispensing

      Mist is dispensed to the chambers by impingement of solutions on nozzles producing droplets ranging from 50-100 um in diameter, which are similar in size to those of fog. Misting is not automated.

      (2) Chemical Analysis and Application Rate

      Chemical analyses of the incident mist and throughfall are extensive and include pH, conductivity, inorganic anions and cations, carbohydrates, proteins, and amino acids.

      (3) Protocol for Chemical/Temporal Exposure Dynamics

      The exposure protocol is maximized to address the issue of leachate chemistry. All misting is of a 4-h duration, with treatments being 2-3 times within a 72-h period.

   c. Environment Controls

      The study is conducted in a glasshouse providing monitoring and control of photoperiod and irradiance. During the misting events, the temperature and irradiance are monitored and controlled.

   d. Data Acquisition

      Not described.

Diagram of the system is not available.

Communication: Taylor, G. E., Jr. Carbon dioxide assimilation and growth of red spruce (Picea rubens Sarg.) seedlings in response to ozone, precipitation chemistry, and soil type. Personal communication.

Location: Oak Ridge National Laboratory, Oak Ridge, Tennessee

Summary: The system is metal-framed and wrapped in polyethylene on all sides to form an enclosure. The system is portable, with use limited by the power source for the dispenser. It is currently located in a glasshouse on growth benches. During the non-exposure periods, the enclosure is removed from the bench to eliminate heat buildup.

1. Hardware

   a. Description

      The unit is 1.1 m long, 1.0 m wide, and 1.2 m high. The platform area is 1.1 m^2 with 1.2 m height. There are four units independently operated and positioned side by side on a bench. Root zone manipulation is possible as part of the design.

   b. Methodology

      (1) Dispensing

         Solution is atomized by rotating-disc impaction and forced-air delivery; deposition is via gravity and interception. Duration of events and the number of events per experimental duration can be automated.

      (2) Chemical Analysis and Application Rate

         Deposition rate is adjusted to simulate ambient conditions. Rate of deposition is total interception of cloud water by foliage, stem, and pot individually as determined by gravimetric method. Evaluation of deposition chemistry includes onsite analysis of H^+ concentration, with a more detailed description of cations and anions via intermittent ICP analysis.

      (3) Protocol for Chemical/Temporal Exposure Dynamics

         Chemistry is based upon reported chemical composition of cloud water. Temporal aspects are based upon reported frequency in high elevation forests.

   c. Environment Controls

      Glasshouse air is cooled by evaporative coolers, heated with steam, and charcoal filtered. Water is distilled and deionized. Monitoring of glasshouse atmosphere is not routine except for temperature, photoperiod, and relative humidity.

d. Data Acquisition

Not described.

2. Performance Evaluation

a. Wet Deposition Event

Coefficient of variation for distribution uniformity is 49%.

b. Wet Deposition Environment

Not described.

c. Non-Exposure Growth Environment

Only radiation and temperature are reported; ozone levels are $\leq$ 0.5 x ambient.

d. Deposition Parameters

Coefficient of variation for foliar interception is 100% among plants. Coefficient of variation for soil deposition rate is 49%.

Diagram of system is not available.

Publication: Van Voris, P. (publication date not reported). The toxic aerosol research facility at Battelle's Pacific Northwest Laboratories. Facility and Equipment. Battelle Pacific Northwest Laboratories, Richland, WA.

Location: Battelle Pacific Northwest Laboratories, Richland, Washington

Summary: This aerosol exposure system is a modified special wind tunnel that is sealed, recirculating, and designed for total P-3 containment. The exposure cells provide controlled environments for plant exposure and the facility is serviced by an analytical support laboratory. The system provides computerized control of, and data acquisition for, the wind tunnel exposure environment that includes temperature, vapor pressure deficit, illumination, wind speed, gas species concentrations, and airborne contaminant quality and quantity. The entire system operates under negative pressure to ensure containment of toxic chemical species.

1. Hardware

   a. Description

      The wind tunnel is constructed of stainless steel, except for the transparent Lexan walls and ceilings of the exposure cells. The test section is 6.1 m long, 0.6 m in high, and 0.6 m wide. Wind speeds of 0 to 65 mph are attainable in the exposure cells.

   b. Methodology

      (1) Dispensing

      The principal methods of aerosol generation are a vibrating orifice (1 to 3 um) and a submicron generator that produces monodisperse aerosols (0.04 to 1.0 um).

      (2) Chemical Analysis and Application Rate

      Multiple intrusive and non-intrusive techniques for characterizing the physical features of the aerosols are outlined. Chemical analysis of collected aerosols is reportedly achieved following size fractionation of the aerosol mass. Techniques for chemical analysis are not reported. Techniques for characterizing foliar deposition rates are not reported.

      (3) Protocol for Chemical/Temporal Exposure Dynamics

      Chemistry of selected aerosols is not reported.

c. Environment Controls

Air is filtered and conditioned for control of temperature, vapor pressure deficit, aerosol concentration, and concentration of trace and physiologically-important gases. Conditioning is computer controlled.

d. Data Acquisition

Data acquisition is provided by a dedicated computer.

2. Performance Evaluation

Data are not described.

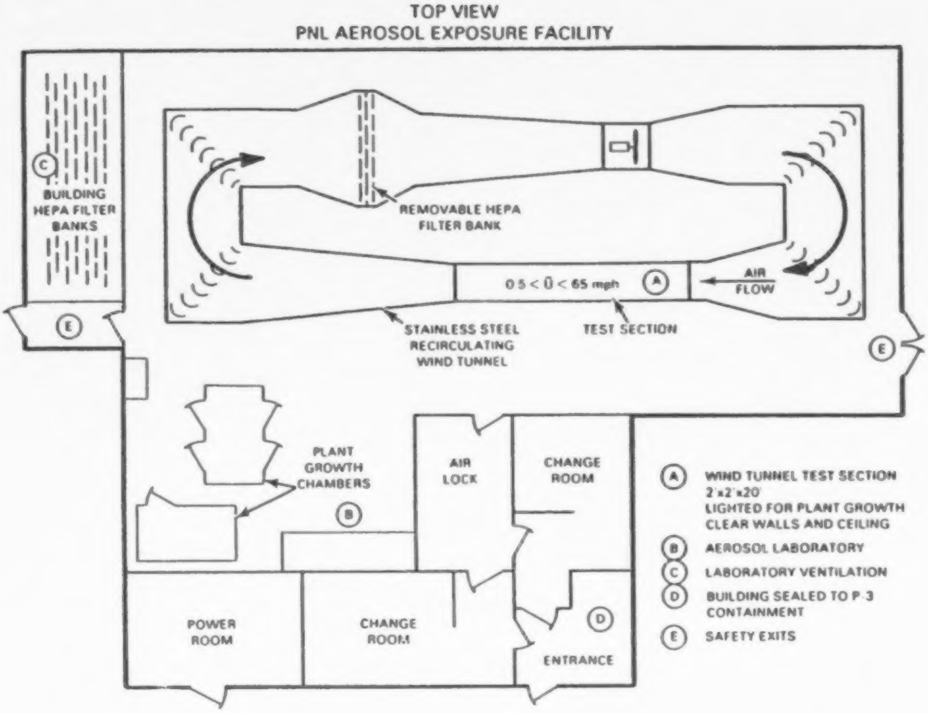

TOP VIEW
PNL AEROSOL EXPOSURE FACILITY
Ⓒ
BUILDING HEPA FILTER BANKS
REMOVABLE HEPA FILTER BANK
$0.5 < \bar{U} < 65$ mph
Ⓐ
AIR FLOW
STAINLESS STEEL RECIRCULATING WIND TUNNEL
TEST SECTION
Ⓔ
Ⓔ
PLANT GROWTH CHAMBERS
Ⓑ
AIR LOCK
CHANGE ROOM
POWER ROOM
CHANGE ROOM
Ⓓ
ENTRANCE
Ⓐ WIND TUNNEL TEST SECTION 2'x2'x20' LIGHTED FOR PLANT GROWTH CLEAR WALLS AND CEILING
Ⓑ AEROSOL LABORATORY
Ⓒ LABORATORY VENTILATION
Ⓓ BUILDING SEALED TO P-3 CONTAINMENT
Ⓔ SAFETY EXITS

Figure G-1. Top view of Toxic Aerosol Exposure Facility showing recirculating wind tunnel and building air filter systems (reprinted with permission of Battelle Pacific Northwest Laboratories).

Publication: Wood T., and F. H. Bormann. 1974. The effects of artificial acid mist upon the growth of Betula alleghaniensis Britt. Environ. Pollut. 7:259-268.

Additional Publication: Wood, T., and F. H. Borman. 1975. Increases in foliar leaching caused by acidification of an artificial mist. Ambio 4:169-171.

Location: Yale University, New Haven, Connecticut

Summary: This is an inexpensive system for investigating the potential effects of acid mist on foliar leaching and growth processes. The system is situated in a glasshouse environment and is suitable for administering mist solutions to low stature plants maintained in pots on glasshouse benches. Both crops and forest tree seedlings have been used with this system.

1. Hardware

a. Description

No specifications or design features reported.

b. Methodology

(1) Dispensing

Mist solutions are delivered under positive pressure to impingement-type fog nozzles. The degree to which the system is automated is not reported.

(2) Chemical Analysis and Application Rate

The acidity of the mist is measured electrometrically, although it is not clear whether the measurement is on the stock solution or on the deposited mist in a collection vessel. The concentration of other cations and anions are not measured since the only chemical adjustment to the deionized water is sulfuric acid. The application rate is measured by estimating deposition to an empty pot. There is no estimate of foliar interception.

(3) Protocol for Chemical/Temporal Exposure Dynamics

The chemistry of the mist solution is adjusted solely to reflect acidity, with the adjustment of deionized water pH being achieved through the addition of sulfuric acid. The temporal features of the misting are at the discretion of the experimental design and were 6 h wk^{-1} with the rate of deposition being 0.5 cm wk^{-1} pot. This rate is roughly 20% of that deposited in rainfall in the Northeast.

c. Environment Controls

The system exists in a glasshouse environment, and the degree of environmental monitoring and control is reported only for the photoperiod.

d. Data Acquisition

Not described.

Diagram for system is not available.

II. OUTDOORS

Publication: Reiners, W. A., and R. K. Olson. 1984. Effects of canopy components on throughfall chemistry: An experimental analysis. Oecologia 63:320-330.

Location: Dartmouth College, Dartmouth, New Hampshire

Summary: This system is designed for field or laboratory studies focusing on the basic mechanisms governing the chemical flux and fate of principal ions in deposited rain as they come in contact with vegetation. Consequently, the focus is on the exchange of ions between the rain and vegetation components as a function of water flow over vegetation surfaces, duration of rainfall exposure, and temporal duration of antecedent dry deposition period. The analytical basis is mass balance calculations of input and output chemistry including the incident simulated rain, throughfall, and stemflow. The flux estimates on an ion-specific basis take into account vegetation surface area (e.g., needle, twigs, and epiphyte coverage) and rate of rainfall application. Only one level of rainfall acidity was selected (pH 4.08), which approximated ambient rainfall pH.

1. Hardware

a. Description

Artificial rain is applied to live branches in the field and dead branches in the lab. The only dimension figure provided is the 0.5-m height of the nozzle above the vegetation. The entire apparatus is shielded from incident ambient rain and particle deposition by a clear plastic sheet erected 1 m above the branches. Access is provided by a wooden observation platform.

b. Methodology

(1) Dispensing

Artificial rain is applied from a nozzle positioned 0.5 m above the branches. The solution is under positive pressure, and the application rate is regulated by manipulations of pressure and the timing of spray bursts by an electric valve and timer. The rate of application ranges from 0.3 to 3.5 cm h^{-1}.

(2) Chemical Analysis and Application Rate

The chemistry of incident rain (deposited rain, not the stock solution), stemflow, and throughfall is characterized with respect to pH (within 24 h), ammonium/nitrate/sulfate (Autoanalyzer), and sodium/potassium (flame photometry). The application rate is characterized by collecting the drip from branches in a 0.2-m diameter funnel positioned below the rain application device.

(3) Protocol for Chemical/Temporal Exposure Dynamics

The exposure dynamics are pre-scheduled in accordance with the experimental design. The chemistry of the rain simulant is comparable to the volume-weighted summertime average rain for Mt. Moosilauke in New Hampshire, and includes adjustments for pH, conductivity, total ion composition, and specific activity. The duration of the rainfall event and the duration of the intervening dry period are deliberately varied in the study.

c. Environment Controls

Temperature in the field is recorded.

d. Data Acquisition

Not described.

Diagram of the system is not available.

Publication: Skeffington, R. A., and T. M. Roberts. 1985. The effects of ozone and acid mist on Scots pine saplings. Oecologia 65:201-206.

Location: Central Electricity Generating Board, Leatherhead, Surrey, England

Summary: This system consists of four individually-operated "Solardome" units which provide an automated system for investigating chronic effects of gaseous pollutants on agricultural crop and forest tree species. The Solardomes are suitable for potted plants maintained for long term periods. This facility was used for the reported study solely with mist interception.

1. Hardware

   a. Description

      The solardome volume is 35 m^3. There are four units, individually operated. Root zone manipulation is a deliberate part of the design. Other forms of wet and dry deposition can be studied; a major thrust of the research is pollutant interactions.

   b. Methodology

      (1) Dispensing

         The method of dispersing is by means of ASL "Killaspray 8" spray gun. Dispensing is manual.

      (2) Chemical Analysis and Application Rate

         Throughfall is collected weekly and measured immediately for hydrogen ion concentration; other cations and anions are measured via ICP or autoanalyzer. Method for deposition rate is not specified.

      (3) Protocol for Chemical/Temporal Exposure Dynamics

         Chemistry of mist adjusted for sulfur and nitrogen ratio to yield desired pH. Mist application at 0900 and 1630 h daily 5 d wk^{-1} at a rate sufficient to saturate foliage.

   c. Environment Controls

      Charcoal-filtered air is used. Pollutant levels are monitored and controlled. Above-canopy wind velocity is controlled.

   d. Data Acquisition

      Dry deposition data and environmental conditions are logged.

2. Performance Evaluation

a. Wet Deposition Event

Chemistry of stock solution is reported. Distribution uniformity is assessed qualitatively.

b. Wet Deposition Environment

Mean wind velocity 0.5 m/s.

c. Non-Exposure Growth Environment

Air mixing, turnover time, trace pollutant levels. and soil pH are reported.

d. Deposition Parameters

Throughfall chemistry, soil deposition rate, and deposition chemistry are reported.

Diagram of the system is not available.

Publication: Thorne, P. G., G. M. Lovett, and W. A. Reiners. 1982. Experimental determination of droplet impaction on canopy components of balsam fir. J. Appl. Meteorol. 21:1413-1416.

Additional Publication: Lovett, G.M., W. A. Reiners, and R. K. Olson. 1982. Cloud droplet deposition in subalpine balsam fir forests: Hydrologic and chemical inputs. Science 218:1303-1304.

Location: Dartmouth College, Dartmouth, New Hampshire

Summary: This system is a closed-circulation wind tunnel capable of providing wind speeds $\geq$ 800 cm s^{-1}. The system is most suitable for investigating the biological (e.g., vegetation surface features) and physical factors governing the impaction of cloud droplets on components of vegetation canopies. The system utilizes a tracer -- monodispersed glycerin droplet -- tagged with uranine (sodium fluorescein), with the deposition rate being quantified by the intensity of fluorescence. The mass of the glycerin droplet is set to a comparable mass of that of cloud water droplets. The comparability in behavior of the glycerin droplet relative to that of a typical cloud water droplet is evaluated empirically in the wind tunnel. The capture efficiency of vegetation components may differ as a function of needle-cluster morphology. The conclusion is that capture efficiency of twigs of different sizes and needle-bearing branches is explainable by a single empirically-derived mathematical expression so that the data may be applicable to a broader range of component configuration.

1. Hardware

a. Description

The closed circulation wind tunnel has an internal test platform measuring 0.15 m in length and 0.21 by 0.21 m set perpendicular to the flow. The maximum wind speed is 810 cm s^{-1} but experimental runs were conducted at speeds of 30, 170, 340, and 725 cm s^{-1}.

b. Methodology

(1) Dispensing

Glycerin droplets are formed by a vibrating orifice aerosol generator dispersed 0.5 m upstream of the test platform. Methods for automation are not reported.

(2) Chemical Analysis and Application Rate

Methods for analyzing the chemistry of the hydrometeor are not applicable to this study or system. The method to evaluate the capture efficiency of glycerin droplets is to remove by elution with water the fluorescein tag from vegetation components and subsequently quantify the amount of fluorescence in solution. The flux rate is calculated on a projected or geometric area basis taking into account time of exposure in the wind tunnel.

(3) Protocol for Chemical/Temporal Exposure Dyanmics

The chemistry of the droplet is not a variable in this study. The exposure dynamics are not relevant except as related to the wind speed component that effects impaction of droplets to boles, twigs, needles, and epiphytes.

c. Environment Controls

Wind speed is monitored and controlled.

d. Data Acquisition

Not described.

Diagram of the system is not available.

APPENDIX H

Description of Facilities and Performance Evaluation -- Systems for Dust and Particulate Exposure Research

Reference: Darley, E. F., S. Lerman, and R. J. Oshima. 1968. Plant exposure chambers for dust studies. J. Air Pollut. Contr. Assoc. 18:28-29.

Location: Statewide Air Pollution Research Center, Riverside, California

Summary: A description is given of plant exposure chambers which provide for uniform application of dusts at rates simulating those of natural conditions. One set of chambers receives artificial light and is used for short-term exposures. A second set of larger chambers receives natural light and provides for dusting plants daily to maturity.

1. Hardware

Chambers are constructed of plexiglas or Tedlar film-covered wooden frames. A feeder assembly from a Bacho Microparticle Classifier serves as the means of introducing the dust at the top of the chamber. A whirling, counter-airflow stream is introduced several centimeters below the feed nozzles to assist in lateral distribution of the dust. Distribution is further enhanced by placing exposed plants on a turntable. Carbon-filtered auxiliary air is supplied through a distribution system below the turntable.

a. Chambers

Two sizes of chambers have been developed that operate in the same manner. The smaller chambers, measuring 75 cm^2 by 105 cm high and made of plexiglas, are used for short-term exposures where plants are dusted for no more than a few days. The larger chambers, measuring 135 cm^2 by 180 cm high, consist of a wooden frame covered with Tedlar film, and are used for dusting plants daily until they reach maturity.

b. Pollutant Dispensing and Monitoring

Dust is introduced at the top of the chamber by means of a feeder assembly from a Bacho Microparticle Classifier. This vibrated-hopper, brush-fed system meters dust at very low rates. Uniform distribution of dust on leaves is accomplished by a combination of an air distributor near the top of the chamber and a turntable (1 rpm) plant stage near the floor. As the dust drops from the feed nozzle, just inside the chamber, it encounters vertical and lateral air flow provided by the air distributor.

c. Data Acquisition

Not described.

d. Environment Controls

The small chambers are located in a darkened room and light is supplied, through a water bath, by four 300 W cool-beam lamps placed over the chamber. The larger chambers are in a greenhouse with natural light. In the smaller chambers, filtered air is piped in at floor level and discharged through a circular manifold below the plant stage, with air exchange once every 4 minutes. Auxiliary air for the large chamber is supplied to a plenum chamber below the floor with entry through a circular arrangement of holes. Air is exhausted through small holes located near the top of the chamber walls with air exchange from 1 to 1.5 per minute.

2. Performance Evaluation

a. Pollutant Uniformity

Deposition on the outer two-thirds of the revolving stage did not vary by more than 5%. Deposits closer to the center varied by as much as 15%.

b. Environment Uniformity

Not described.

c. Pollutant Control and Maintenance

Not described.

d. Environment Control and Maintenance

Not described.

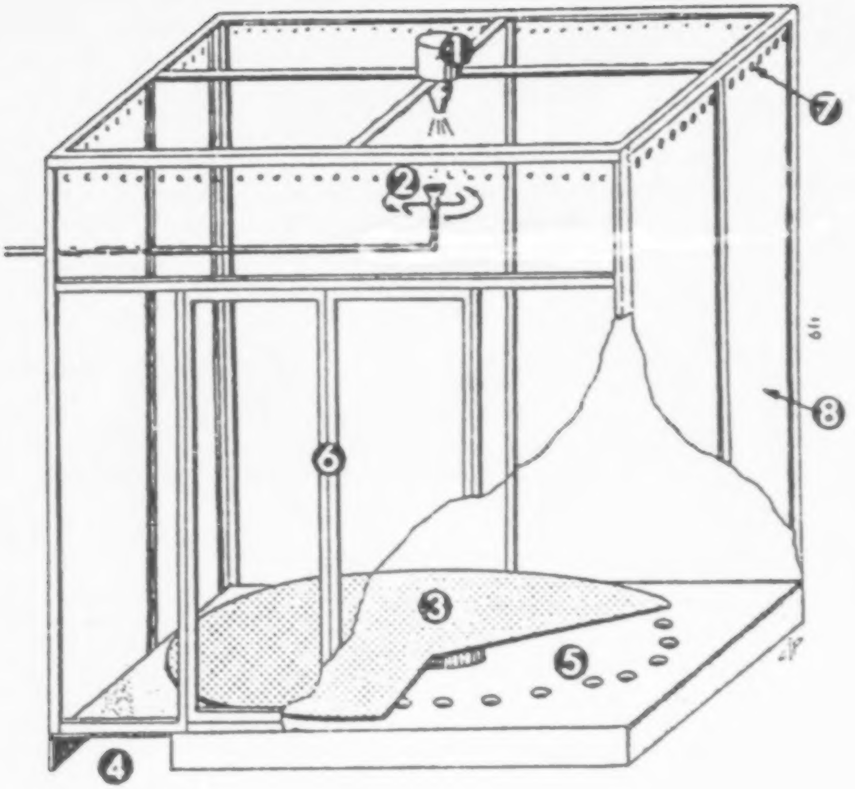


Figure H-1. Large dusting chamber. Dust is dispensed with a Bacho feeder assembly (1) and drops into the chamber against a whirling counter-flow air stream (2). This action, coupled with the turntable plant stage (3) provides for uniform dust deposit. Auxiliary air from an activated carbon filter-cooler enters a plenum (4) and is discharged into the chamber below the plant stage (5). Doors (6), vent holes (7), and Tedlar film walls (8) are indicated (reprinted from Darley et al., 1968, with permission of the Air Pollution Control Association).

Reference: Ormrod, D. P., J. C. Hale, O. B. Allen, and P. J. Laffey. 1986. Joint action of particulate fallout, nickel, and rooting medium nickel on soybean plants. Environ. Pollut. (Series A) 41:277-291.

Location: University of Guelph, Guelph, Ontario, Canada

Summary: A plexiglas chamber for particulate deposition is described. An air stream into the top of the chamber carries particulate that drops on plants.

1. Hardware

This chamber is based on the one described by Marple and Rubow (1983). The chamber is constructed of plexiglass. A tube carries an air stream into the top of the chamber. Particulate is introduced from a side arm.

a. Chambers

Dimensions are 38 cm^2 and 152 cm high. The chamber can accommodate 4 plants at a time. A 1.5-cm diameter tube carries an air stream into the top of the chamber. A perforated deflector directs the air flow downwards and a baffle is placed across the chamber to linearize the flow of air and particulate for a more even and gentle deposition on the plants.

b. Pollutant Dispensing and Monitoring

Particulate is introduced from a side arm with a burst of air injected into the air stream that is moving into the top of the chamber. A range of experimental concentrations is provided by introducing weighed amounts of particulate.

c. Environment Controls

The chamber is set in a fume hood in an air-conditioned laboratory.

d. Data Acquisition

The particulate dose to each plant is estimated by analysis of leaves for metal. Estimated dosage is the assayed metal concentration in and on the leaves multiplied by the leaf dry weight and divided by the estimated leaf area at time of treatment.

2. Performance Evaluation

a. Pollutant Uniformity

Distribution of particulate was evaluated with filter paper simulated leaves and intact leaves. Position had a significant effect on deposition so sufficient replicates were conducted to eliminate variation due to position in statistical analyses.

b. Environment Uniformity

Not described.

c. Pollutant Control and Maintenance

Not applicable.

d. Environment Control and Maintenance

Not described.

Diagram of the system is not available.

APPENDIX I

Supplementary Reports:

Some Basic Exposure Techniques

Reference: Heagle, A. S., and R. B. Philbeck. 1978. Exposure techniques. In: W. W. Heck, S. V. Krupa, and S. N. Linzon (eds.). Handbook of Methodology for the Assessment of Air Pollution Effects on Vegetation, Air Pollution Control Association, Pittsburgh. pp. 6-1 - 6-19.

Summary: This report outlines some basic principles for exposing plants to prescribed amounts of gaseous pollutants so that the results will be meaningful and acceptable to others. Exposure system design, dispensing systems, pollutant control systems, and time-sharing monitoring are discussed.

Recommendations:

1. Chamber Requirements

   a. Uniform Distribution of Concentration

   A mean deviation of less than 10% should be acceptable for low concentration studies and of less than 5% for high concentration studies.

   b. Uniform Environment

   Variations in temperature of ± 0.5°C, relative humidity of ± 3%, irradiance of ± 0.5 Klux, and air velocity of ± 1 m min^{-1} are generally attainable and possibly satisfactory for most uses. A plan of random distribution of plants is advised as well as, in long-term studies, changing the position of plants and the assignment of treatments to chambers.

   c. Non-Reactive Surfaces

   Chamber surfaces should be covered with the most nonreactive materials available.

   d. Precise Control of Pollutant Concentrations

   Common gaseous pollutants can be controlled accurately to within ± 0.01 ppm for low concentrations and ± 0.02 ppm for high concentrations.

   e. Environment Resembling Ambient Conditions

   Ranges of values are recommended for experimental use based on occurrences in ambient air during plant growth and factors that affect response of plant to oxidants.

   f. Single-Pass System

   Single-pass flow systems are recommended.

g. Negative Pressure

Recommended as precaution against leakage of gases into greenhouse or laboratory air.

h. Easily Portable

An important consideration only in certain field situations.

i. Transparent Covering

Clear teflon film is preferred to all other coverings.

j. Chamber Calibration

Comparisons are required of pollutant concentration and environmental levels within and between chambers in the same system to ensure uniformity.

2. Basic Components of Acceptable Systems

a. Greenhouse Chambers

-- Exhaust air blower with charcoal filter to draw air through system.

-- Inlet equipped with charcoal filter.

-- Inlet and exhaust system for each chamber.

-- Dispensing and monitoring system connected by teflon tubing.

-- Lights.

-- Cooling mechanisms for summer use.

b. Controlled Environment Chambers

-- As above except provide temperature, humidity, and light control systems.

c. Dispensing Systems

-- Deliver easily-controllable concentrations to one or more chambers.

-- Free of leaks.

-- Relatively free of concentration drift.

-- Constructed with nonreactive materials.

d. Pollutant Control Systems

-- Control depends on experimental objectives.

-- Time-sharing monitoring may be used depending on the response time of the monitor, and the degree of variability of the pollutant concentration.

APPENDIX J

Supplementary Reports:

Recommended Environmental Monitoring Protocol --

Controlled Environment Guidelines

Controlled-environment Guidelines

Donald T. Krizek[1]
Plant Stress Laboratory, U.S. Department of Agriculture, ARS,
Beltsville, MD 20705

J. Craig McFarlane[2]
Corvallis Environmental Research Laboratory, Environmental Protection
Agency, Corvallis, OR 97330

Since publication of the "Guidelines for Measuring and Reporting the Environment for Plant Studies" in *HortScience* (2, 3, 4, 6), the guidelines have been refined, reviewed, and published in various journals (1, 7, 8, 9, 10, 11, 13, 14, 15).

In the course of this review process, several changes have been made by the North Central Region (NCR-101) Technical Committee on Growth Chamber Use since formal presentation of the guidelines at a workshop in Madison, Wis., in 1979 (16). These changes have been adopted by the ASHS Working Group on Growth Chambers and Controlled Environments and are presented here to bring members of ASHS up to date.

Underlying most of the changes is the recognized need to adopt SI units of measurement in their entirety (5, 12). The changes, with the rationale for each change, are shown in Table 1. The guidelines as currently recommended are presented in Table 2.

Adoption of these modified guidelines by researchers and adherence to these recommendations by journal reviewers and editors should facilitate comparison of experimental results obtained in controlled-environment studies on a worldwide basis.

Received for publication April 27, 1983. The cost of publishing this paper was defrayed in part by the payment of page charges. Under postal regulations, this paper therefore must be hereby marked *advertisement* solely to indicate this fact.

[1] Plant Physiologist, Plant Physiology Institute, Rm. 206, B-001, BARC-W, Beltsville, MD 20705.

[2] Plant Physiologist, 200 S.W. 35th St., Corvallis, OR 97330.

Table 1. Current changes in controlled-environment guidelines.

Parameter	Former unit	Present unit	Rationale
photosynthetic photon flux density (PPFD)	$\mu E\ s^{-1}\ m^{-2}$	$\mu mol\ s^{-1}\ m^{-2}$	The mol is the accepted SI unit.
watering	L	l	SI convention.
nutrition	solid media $kg\ m^{-3}$	solid media $mol\ m^{-3}$ or $mol\ kg^{-1}$	The mol is the accepted SI unit for concentration.
electrical conductivity	footnote $1\ dSm^{-1} =$ $1\ mho\ cm^{-1}$	footnote $1\ dSm^{-1} =$ $1\ mmho\ cm^{-1}$	Initial error in conversion factor.

Table 2. Guidelines for measuring and reporting environmental conditions in controlled environments.[z]

Parameter	Typically used unit	Measurements Where to take	 When to take	 What to report
Radiation				
Photosynthetically active radiation (PAR) a) Photosynthetic photon flux density (PPFD) 400–700 nm with cosine correction.	$\mu mol\ s^{-1}\ m^{-2}$ [y] or $\mu E\ s^{-1}\ m^{-2}$	At top of plant canopy. Obtain average over plant growing area.	At start and finish of each study and biweekly if studies extend beyond 14 days.	Average over containers at start of study. Decrease or fluctuation from average over course of study. Wavebands measured.
or b) Photosynthetic Irradiance (PI) 400–700 nm with cosine correction.	$W\ m^{-2}$			
Total irradiance With cosine correction. Indicate bandwidth.	$W\ m^{-2}$	At top of plant canopy.	At start of each study.	Average over containers. Wavebands measured.
Spectral distribution a) Spectral photon flux density λ_1–λ_2 nm in < 20 nm bandwidths with cosine correction.	$\mu mol\ s^{-1}\ m^{-2}\ nm^{-1}$ (λ_1–λ_2 nm) (quanta)	At top of plant in center of growing area.	At start of each study as a minimum.	Spectral distribution of radiation with integral (λ_1–λ_2) at start of study. Source of radiation and instrument/sensor.
or b) Spectral irradiance (Spectral energy flux density) λ_1–λ_2 in < 20 nm bandwidths with cosine correction.	or $Wm^{-2}\ nm^{-1}$ (λ_1–λ_2 nm)			
Illuminance[x] 380–780 nm with cosine correction	klx	At top of plant canopy.	At start of each study.	Average over containers. Wavebands measured.
Temperature				
Air Shielded and aspirated ($\geq 3\ m\ s^{-1}$) device	°C	At top of plant canopy. Obtain average over plant growing area.	Hourly over the period of the study. (continuous measurement advisable).	Average of hourly average values for the light and dark periods of the study with range of variation over the growing area.
Soil or liquid	°C	In center of container.	Hourly during the first 24 hr of the study. Start immediately after watering (monitoring over the course of the study advisable).	Average of hourly average values for the light and dark periods for the first day or over entire period of the study if taken. Location of measurement.
Atmospheric moisture				
Shielded and aspirated ($\geq 3\ m\ s^{-1}$) psychrometer, dew point sensor or infrared analyzer	% RH, dewpoint temperature, or $g\ m^{-3}$	At top of plant canopy in center of plant growing area.	Once during each light and dark period, taken at least 1 hr after light changes. Monitoring over the course of the study advisable.	Average of once daily readings for both light and dark periods with range of diurnal variation over the period of the study (or average of hourly values if taken).

Table 2. (continued).

Parameter	Typically used unit	Measurements		
		Where to take	When to take	What to report
Air velocity	$m\ s^{-1}$	At top of plant canopy. Obtain maximum and minimum readings over plant growing area.	At start and end of studies. Take 10 successive readings at each location and average.	Average and range of readings over containers at start and end of the study.
Carbon dioxide	$mmol\ m^{-3}$	At top of plant canopy.	Hourly over the period of the study.	Average of hourly average readings and range of daily average readings over the period of the study.
Watering	l	—	At times of additions.	Frequency of watering. Amount of water added per day and/or range in soil moisture content between waterings.
Substrate	—	—	—	Type of soil and amendments. Components of soilless substrate. Container dimensions.
Nutrition	Solid media: $mol\ m^{-3}$ or $mol\ kg^{-1}$ Liquid culture: μ or $mmol\ l^{-1}$	—	At times of nutrient additions.	Nutrients added to solid media. Concentration of nutrients in liquid additions and solution culture. Amount and frequency of solution addition and renewal.
pH	pH units	In saturated media, extract from media, or solution of liquid culture.	Start and end of studies in solid media. Daily in liquid culture and before each pH adjustment.	Mode and range during study.
Electrical conductivity	$dS\ m^{-1}$ [w] (decisiemens per meter)	In saturated media, extract from media, or solution of liquid culture.	Start and end of studies in solid media. Daily in liquid culture.	Average and range during study.

Literature Cited

1. American Society of Agricultural Engineers. 1982. ASAE Engineering Practice: ASAE EP411. Guidelines for measuring and reporting environmental parameters for plant experiments in plant growth chambers, p. 406–409. In: 1982 Agricultural Engineers Yearbook, Amer. Soc. Agr. Eng., St. Joseph, Mich.
2. American Society for Horticultural Science—Committee on Growth Chamber Environments. 1972. Guidelines for reporting studies conducted in controlled environment chambers. HortScience 7:239.
3. American Society for Horticultural Science—Working Group on Growth Chambers and Controlled Environments. 1980. Guidelines for measuring and reporting the environment for plant studies. HortScience 15:719–720.
4. Berry, W.L., P.A. Hammer, R.H. Hodgson, D.T. Krizek, R.W. Langhans, J.C. McFarlane, D.P. Ormrod, H.A. Poole, and T.W. Tibbitts. 1977. Revised guidelines for reporting studies in controlled environment chambers. HortScience 12:309–310.
5. Incoll, L.D., S.P. Long, and M.R. Ashmore. 1977. SI units in publications in plant science. Current Adv. Plant Sci. 28:331–343.
6. Krizek, D.T. 1970. Proposed guidelines for reporting studies conducted in controlled environment chambers. HortScience 5:390.
7. Krizek, D.T. 1982. Guidelines for measuring and reporting environmental conditions in controlled environment studies. ASPP Newsletter 9(6):7–8.
8. Krizek, D.T. 1982. Guidelines for measuring and reporting environmental conditions in controlled-environment studies. Physiol. Plant. 56:231–235.
9. Krizek, D.T. 1983. Controlled-environment studies, p. 170. In: Council of Biology Editors. The CBE Style Manual, 5th ed. Council of BE, Bethesda, Md.
10. McFarlane, J.C. 1981. Measurement and reporting guidelines for plant growth chamber environments. Plant Science Bul. 27(2):9–11.
11. McFarlane, J.C. 1982. Letter to the editor: measurement and reporting guidelines for plant growth chamber environments. J. Envir. Qual. 11:719–720.
12. National Bureau of Standards (NBS). 1981. The international system of units. NBS Special Pub. 330. Washington, D.C.
13. Sager, J.C. 1982. Guidelines for measuring and reporting environmental parameters for plant experiments in growth chambers. ASAE Paper No. 82-4056. ASAE Environment of Plant Structures (SE-303) Committee. St. Joseph, Mich.
14. Spomer, L.A. 1980. Guidelines for measuring and reporting environmental factors in controlled environment facilities. Commun. Soil Sci. & Plant Anal. 11:1203–1208.
15. Spomer, L.A. 1981. Guidelines for measuring and reporting environmental factors in growth chambers. Agron. J. 73:376–378.
16. Tibbitts, T.W. and T.T. Kozlowski. 1979. Controlled environment guidelines for plant research. Academic Press, New York.

---

[y] The first is preferred because it follows the SI convention. However, since 1 Einstein = 1 mol of photons, the values are equivalent. It is inaccurate to report that "radiation values are *xx.x* $\mu mol\ s^{-1} m^{-2}$," for the same reason that reporting $mol\ kg^{-1}$ is wrong without associating that value and units with the element (i.e., K was 300 $mol\ kg^{-1}$). Thus, "the PFFD was 320 $\mu mol\ s^{-1}\ m^{-2}$" is correct since it specifically associates a definition (i.e., photons within a certain waveband) with the value and units.

[x] Report with PAR reading *only* for historical comparison.

[w] 1 $dS\ m^{-1}$ = $mmho\ cm^{-1}$.

APPENDIX K

Supplementary Reports:

Suggested Measurements and Reporting Characteristics of Dry Deposition Gaseous Exposure Systems

Suggested Measurements for Characterization of Dry Deposition Gaseous Exposures (all measurements at plant height unless otherwise indicated)

1. Non-Chamber Plume Exposures

A. Atmospheric Chemistry
(1) Gaseous Pollutant
a. Distribution
(i) Horizontal -- continuous at many points in a grid over plot.
(ii) Vertical -- spot checks ≥ 2 heights.
b. Temporal Patterns
-- Continuous at many points.
(2) Non-Pollutant Chemicals
a. Water Vapor (Humidity)
-- Continuous at 1 point in ambient air.
b. CO_2
-- None.

B. Physical Properties of the Atmosphere
(1) Irradiance (Quantum Level at 400-700 nm)
a. Distribution
-- None.
b. Temporal Patterns
-- Continuous at 1 point in ambient air.
(2) Heat Energy (Air Temperature)
-- Continuous at 1 point in ambient air.
(3) Air Movement
-- None, N/A (not applicable).

C. Soil Temperature
-- None, N/A.

D. Air Exchanges
-- None, N/A.

2. Non-Chamber Air Exclusion Systems

A. Atmospheric Chemistry
(1) Gaseous Pollutant
a. Distribution
(i) Horizontal -- Spot checks at many points linearly along ducts.
(ii) Vertical -- Continuous at ≥ 2 heights.
b. Temporal Patterns
-- Continuous at 1 point per system.
(2) Non-Pollutant Chemicals
a. Water Vapor (Humidity)
-- Continuous at 1 point in ambient air.
b. CO_2
-- None.

B. Physical Properties of the Atmosphere
   (1) Irradiance (Quantum Level at 400-700 nm)
      a. Distribution
         -- None.
      b. Temporal Patterns
         -- Continuous at 1 point in ambient air.
   (2) Heat Energy (Air Temperature)
      -- Continuous at 1 point in ambient air.
   (3) Air Movement
      -- Spot Checks

C. Soil Temperature
   -- Continuous at 1 point each in outside plot and in system at $\geq$ 0.05 m depth.

D. Air Exchanges
   -- None, N/A.

3. Chambers -- Outdoors

   - A. Atmospheric Chemistry
     - (1) Gaseous Pollutant
       - a. Distribution
         - (i) Horizontal -- Before study at many points in a grid across chamber.
         - (ii) Vertical -- Before study at $\geq$ 4 heights.
       - b. Temporal Patterns
         - -- Continuous at 1 point per chamber or at least every 20 minutes for time-shared monitored systems.
     - (2) Non-Pollutant Chemicals
       - a. Water Vapor (Humidity)
         - -- Continuous at 1 point each in ambient air and 1 chamber.
       - b. CO_2
         - -- None in open chamber, spot checks in closed chamber.

   - B. Physical Properties of the Atmosphere
     - (1) Irradiance (Quantum Level at 400-700 nm)
       - a. Distribution
         - -- Before study in grid across chamber.
       - b. Temporal Patterns
         - -- Continuous at 1 point in ambient air.
     - (2) Heat Energy (Air Temperature)
       - -- Continuous at 1 point each in ambient air and 1 chamber.
     - (3) Air Movement
       - -- Spot checks.

   - C. Soil Temperature
     - -- Continuous at 1 point each in outside plot and 1 chamber at $\geq$ 0.05 m depth.

   - D. Air Exchanges
     - -- Spot checks.

4. Chambers -- Indoors

   - A. Atmospheric Chemistry
     - (1) Gaseous Pollutant
       - a. Distribution
         - (i) Horizontal -- Obtain vertical distributions at sufficient points to characterize horizontal distribution before and after study.
         - (ii) Vertical -- At top of plant canopy and at four levels within the plant canopy including just above the rooting medium, before and after study, and biweekly if studies extend more than 14 days.
       - b. Temporal Patterns
         - -- Continuous at 1 point just above plant canopy or at least every 20 minutes for time-shared monitoring systems.

- (2) Non-Pollutant Chemicals
  - a. Water Vapor (Humidity)
    - -- Continuous at 1 point.
  - b. CO_2
    - -- Spot checks at least biweekly.

B. Physical Properties of the Atmosphere
- (1) Irradiance (Quantum Level at 400-700 nm)
  - a. Distribution
    - -- Before study in grid across chamber.
  - b. Temporal Patterns
    - -- Spot checks at least biweekly at 1 point above plant canopy.
- (2) Heat Energy (Air Temperature)
  - -- Continuous at 1 point.
- (3) Air Movement
  - -- Before study obtain horizontal and vertical distribution.

C. Soil Temperature
- -- Spot checks.

D. Air Exchanges
- -- Spot checks at least biweekly.

Suggestions for Reporting Characteristics of Dry Deposition Gaseous Exposures

1. All Outdoor Systems -- Chamber and Non-Chamber (Measurements at Canopy Height)

    A. Atmospheric Chemistry
        (1) Gaseous Pollutant
            a. Distribution
                (i) Horizontal -- Averages and fluctuation across plant growing area. For plume systems the continuous horizontal averages will be used to assign pollutant doses to specific areas of the plot.
                (ii) Vertical -- Averages at different heights before study.
            b. Temporal Patterns -- Average fluctuation over the entire growing season based on daily time period important to plants, e.g., 12 hours. Significant high values will be reported for ambient concentration. A frequency distribution of concentrations may be included for ambient exposures and plume exposures.
        (2) Non-Pollutant Chemicals
            a. Water Vapor (Humidity)
                -- Average ± fluctuation over the entire growing season for system and ambient air. A graphic presentation of fluctuation is recommended.
            b. CO_2
                -- Vertical and temporal variation based on spot checks in chambers.

    B. Physical Properties of the Atmosphere
        (1) Irradiance (Quantum Level at 400-700 nm)
            a. Distribution
                -- Average ± fluctuation across plant growing area for chambers.
            b. Temporal Patterns
                -- Average ± fluctuation over the entire growing season for system and ambient air. A graphic presentation is recommended.
        (2) Heat Energy (Air Temperature)
            -- Average ± fluctuation over the entire growing season for system and ambient air.
        (3) Air Movement
            -- Average ± fluctuation based on spot checks.

    C. Soil Temperature
        -- Average ± fluctuation over the entire growing season for system and outside plot.

    D. Air Exchanges
        -- Spot checks where applicable.

2. Chambers -- Indoors

- A. Atmospheric Chemistry
  - (1) Gaseous Pollutant
    - a. Distribution
      - (i) Horizontal -- Average ± fluctuation across plant growing area.
      - (ii) Vertical -- Averages at different heights before study.
    - b. Temporal Patterns
      - -- Averages presented graphically if continuously monitored or in tabular form if monitored at 20-minute intervals.
  - (2) Non-Pollutant Chemicals
    - a. Water Vapor (Humidity)
      - -- Follow Krizek and McFarlane (1983).
    - b. CO_2
      - -- Follow Krizek and McFarlane (1983).
- B. Physical Properties of the Atmosphere
  - -- Follow Krizek and McFarlane (1983).

Suggestions for Limits of Exposure and Experimental Variation in Dry Deposition Gaseous Exposures

1. Non-Chamber Plume Exposures

    A. Atmospheric Chemistry
        (1) Gaseous Pollutant
            a. Distribution
                (i) Horizontal -- Maximum ± 10% variation from mean pollutant concentrations at canopy height. May be much greater if system is purposely used as a gradient.
                (ii) Vertical -- Maximum ± 25% variation from 0.3 m above to 0.3 m below top of canopy.
            b. Temporal Patterns
                -- Maximum ± 20%. May be much greater in ambient system.
        (2) Non-Pollutant Chemicals
            a. Water Vapor (Humidity)
                -- No limits.
            b. CO_2
                -- No limits.

    B. Physical Properties of the Atmosphere
        (1) Irradiance (Quantum Level at 400-700 nm)
            a. Distribution
                -- No limits.
            b. Temporal Patterns
                -- No limits.
        (2) Heat Energy (Air Temperature)
            -- No limits.
        (3) Air Movement
            -- N/A

    C. Soil Temperature
        -- No limit.

    D. Air Exchanges
        -- N/A

    E. Ambient Air Exclusion
        -- N/A

2. Non-Chamber Air Exclusion Systems

    A. Atmospheric Chemistry
        (1) Gaseous Pollutant
            a. Distribution
                (i) Horizontal -- Maximum ± 10% variation from mean pollutant concentrations at canopy height.
                (ii) Vertical -- Maximum ± 25% variation.
            b. Temporal Patterns
                -- Maximum ± 10% variation.

- (2) Non-Pollutant Chemicals
    - a. Water Vapor (Humidity)
        - -- No limits.
    - b. CO_2
        - -- No limits.

B. Physical Properties of the Atmosphere
- (1) Irradiance (Quantum Level at 400-700 nm)
    - a. Distribution
        - -- No limits.
    - b. Temporal Patterns
        - -- No limits.
- (2) Heat Energy (Air Temperature)
    - -- Maximum 1°C different from ambient.
- (3) Air Movement
    - -- Maximum 0.5-1.0 m s^{-1} constant air movement with blowers on.

C. Soil Temperature
-- Maximum 1°C different from ambient.

D. Air Exchanges
-- N/A

E. Ambient Air Exclusion
-- At least 70% at canopy height.

3. Chambers -- Outdoors

A. Atmospheric Chemistry
- (1) Gaseous Pollutant
    - a. Distribution
        - (i) Horizontal -- Maximum ± 10% variation from mean polluant concentrations at canopy height.
        - (ii) Vertical -- Maximum ± 10% variation.
    - b. Temporal Patterns
        - -- Maximum ± 10% variation.
- (2) Non-Pollutant Chemicals
    - a. Water Vapor (Humidity)
        - -- Maximum ± 5% variation from ambient.
    - b. CO_2
        - -- No limits.

B. Physical Properties of the Atmosphere
- (1) Irradiance (Quantum Level at 400-700 nm)
    - a. Distribution
        - -- Maximum ± 10% variation from ambient.
    - b. Temporal Patterns
        - -- Maximum ± 10% variation from ambient.
- (2) Heat Energy (Air Temperature)
    - -- Maximum 2°C different from ambient.
- (3) Air Movement
    - -- Maximum 0.5-1.0 m s^{-1} constant air movement with blowers on.

C. Soil Temperature
   -- Maximum 1°C different from ambient.

D. Air Exchanges
   -- Minimum 2-4 air exchanges per minute.

E. Ambient Air Exclusion
   -- At least 70% at canopy height.

4. Chambers -- Indoors

A. Atmospheric Chemistry
   - (1) Gaseous Pollutant
     - a. Distribution
       - (i) Horizontal -- Maximum ± 5% variation from mean pollutant concentrations at canopy height.
       - (ii) Vertical -- Maximum ± 10% variation.
     - b. Temporal Patterns
       - -- Maximum ± 10% variation.
   - (2) Non-Pollutant Chemicals
     - a. Water Vapor (Humidity)
       - -- Maximum ± 5% variation over time from desired level in controlled environments and air conditioned greenhouses.
     - b. CO_2
       - -- Maximum ± 5% variation over time from desired level.

B. Physical Properties of the Atmosphere
   - (1) Irradiance (Quantum Level at 400-700 nm)
     - a. Distribution
       - -- Maximum ± 10% variation from the desired level in controlled environments.
       - -- No limits in greenhouses.
     - b. Temporal Patterns
       - -- Maximum ± 10% variation over the course of the experiment in controlled environments.
       - -- No limits in greenhouses.
   - (2) Heat Energy (Air Temperature)
     - -- Maximum ± 1% variation from the desired level in controlled environments and air conditioned greenhouses.
   - (3) Air Movement
     - -- Maximum 1 m s^{-1} constant air movement.

C. Soil Temperature
   -- Maximum ± 1°C from the desired level.

D. Air Exchanges
   -- Minimum 2-4 air exchanges per minute.

E. Ambient Air Exclusion
   -- At least 95%.

APPENDIX L

Supplementary Reports:

Air Quality Data Bases

Air Quality Data Bases

Criteria Air Pollutants:

The U.S. Environmental Protection Agency established an automated data processing system, SAROAD (Storage and Retrival of Aerometric Data), for the collection and storage of ambient air quality data for several common air pollutants. The data are collected by various federal, state and local air pollution monitoring programs and entered in the SAROAD system.

The data base contains information on a range of compounds that have been measured in the atmosphere but the primary focus is on the criteria air pollutants: ozone, sulfur dioxide, nitrogen dioxide, carbon monoxide, suspended particulate matter and lead. Most of the data are stored as hourly average concentrations but other averaging times have been used. Tapes of the data base can be ordered from the U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, National Air Data Branch, Research Triangle Park, North Carolina.

The USEPA does not collect the air quality data but has established the criteria for acceptable data and submission of the data to SAROAD. Because 100 percent reporting of all monitoring is not required, data for an individual site may range from a few months within the year to essentially all the possible hourly concentration values (8760). Some of the monitoring sites have data for only one or two years while others have a more extended record. The data base contains information concerning both sample site identification and the ambient air quality data for specific pollutants.

Much of the monitoring data in SAROAD has been collected around population or emission-oriented monitoring sites. However, there are approximately 350 ozone monitorings sites (between 1978 and 1984) designated rural or remote; and for sulfur dioxide and nitrogen dioxide, there are 500 and 135 monitoring sites, respectively, that have been designated rural or remote. Usually only one or two compounds are monitored at a given site; consequently, it is difficult to determine how the concentrations of several compounds change, concurrently, over time at a given site.

As part of the Electric Power Research Institute (EPRI) SURE/ERAQS monitoring programs, sulfur dioxide, nitric oxide, ozone, and total suspended particulates were measured at the same sites for part of 1977 and all of 1978 and 1979 at nine sites (Table L-1). The data for the gaseous pollutants are reported as hourly mean concentrations. Most of the sites are in rural locations. Dr. Peter Mueller, Electric Power Research Institute, 3412 Hillview Avenue, Palo Alto, California, can provide information reqarding the data base and the availability of data tapes.

The Tennessee Valley Authority (TVA) has collected ambient air quality data (hourly mean concentrations) primarily in association with their power generation facilities in Alabama, Kentucky, and Tennessee. Sulfur dioxide, ozone, and nitrogen dioxide are reported but not all pollutants have been monitored at all sites. Most sites monitored sulfur dioxide but ozone and/or nitrogen dioxide were monitored at only a few sites. Data are available from

Table L-1. List of EPRI SURE/ERAQS monitoring sites for gaseous air pollutants.[a,b]

Site Location	Latitude (° ' ")	Longitude (° ' ")	Elevation (m)
Montage, MA	42 43 00	72 32 08	73
Scranton, PA	41 35 29	76 04 21	335
Indian River, DE	38 34 50	75 14 45	6
Dundan Falls, OH	39 51 02	81 53 05	250
Rockport, IN	37 52 50	87 03 32	131
Giles County, TN	35 17 06	86 54 07	244
Fort Wayne, IN	41 02 08	85 19 30	244
Research Triangle Park, NC	35 53 00	78 50 03	128
Lewisburg, WV	37 46 27	80 20 00	701

[a] The site locations were originally identified in the Universal Time coordinate system (UTM) and the units have been converted to latitude and longitude; consequently there may be slight differences from the sites identified in the wet deposition data base (Table L-3).

[b] The elevations are approximate; they were obtained from the EPRI wet deposition data base for sites with the same name as in the gaseous air pollution data base.

some sites since the 1970s. However, the sites were frequently in operation for only a few years. Some, but not all, of the TVA data have been submitted to the SAROAD data base. Information on these data bases and data tapes can be obtained from Mr. John Blackwell, Tennessee Valley Authority, Air Quality Branch, 465 Multipurpose Building, Muscle Shoals, Alabama.

Recently (since 1982), the National Park Service initiated an air quality monitoring program in some of the national parks (Table L-2). Ozone, sulfur dioxide, ozone, and nitrogen dioxide are monitored; but not all pollutants have been measured at all sites. Some, but not all of the National Park Service data, have been submitted to the SAROAD data base. Information on the data base and data tapes can be obtained from Mr. Miguel Flores, National Park Service, Air Quality Division, Denver, Colorado.

Wet Deposition:

Wet deposition is the indirect transfer of compounds from the atmosphere to vegetation or the soil surface within or on a hydrometeor (e.g., rain, snow, fog, hail, etc.). A number of studies have attempted to measure and characterize wet deposition. Most of the efforts have focused on rain as the hydrometeor, with studies of deposition via clouds or fog receiving only limited study. Wisniewski and Kinsman (1982) summarized the wet deposition monitoring studies in North America by giving the name of the study, the funding organization, the nature and geographical extent of the study, the type of samples used and the period of operation as well as the location where the chemical analyses were conducted, and the individual to contact for additional information. Although numerous studies were listed, there are only three major wet deposition data bases available. Individual investigators, however, may have additional information.

The most extensive wet deposition monitoring activity in the United States is the National Atmospheric Deposition Network (NADP)/National Trends Network (NTN). Monitoring started in the late 70s and additional sites have been added with time, so that by August 1985, the Network had more than 180 operational monitoring locations distributed across the United States (Figure L-1). Most of the monitoring locations are east of the Mississippi river with a predominance of sites in the Northeast. Precipitation samples are collected weekly and shipped uncooled to a central laboratory where electrical conductivity, pH, SO_4^{2-}, NO_3^-, NH_4^-, Cl^-, PO_4^{3-}, Na^+, K^+, Ca^{2+}, and Mg^{2+} are measured. Dr. Jim Gibson, Program Coordinator, Natural Resource Ecology Laboratory, Colorado State University, Fort Collins, Colorado, should be contacted for information.

The Electric Power Research Institute initiated a wet deposition monitoring program in August 1978. In 1981, the EPRI sites were incorporated in the Utility Acid Precipitation Study Program (UAPSP); currently there are 23 monitoring sites east of the Rockies (Table L-3). In contrast to the NADP program, the precipitation samples (rain and snow) are collected on a daily and/or event basis, cooled in situ and shipped to a central laboratory where pH, SO_4^{2-}, NO_3^-, NH_4^+, Cl^-, Na^+, K^+, Ca^{2+}, and Mg^{2+} are measured. Dr. Peter Mueller, Electric Power Research Institute, 3412 Hillview Avenue, Palo Alto, California, can provide additional information.

Table L-2. National Park Service monitoring sites.

Sites National Park, Site, State	Years
Grand Canyon, AZ	1982-83
Sequoia, Ash Mt., CA	1982-83
Sequoia, Lodgepole, CA	1982-83
Sequoia, Lookout Pt., CA	1983
Everglades, FL	1982-83
Indiana Dunes, IN	1983
Acadia, ME	1982-83
Theodore Roosevelt, ND	1982-83
Congaree Swamp, SC	1981-83
Great Smoky Mt., Elkmont, TN	1980-93
Shenandoah, Dickey Ridge, VA	1983
Shenandoah, Big Meadows, VA	1983
Shenahdoah, Sawmill Run, VA	1983
Olympic, Port Angeles, WA	1981-83

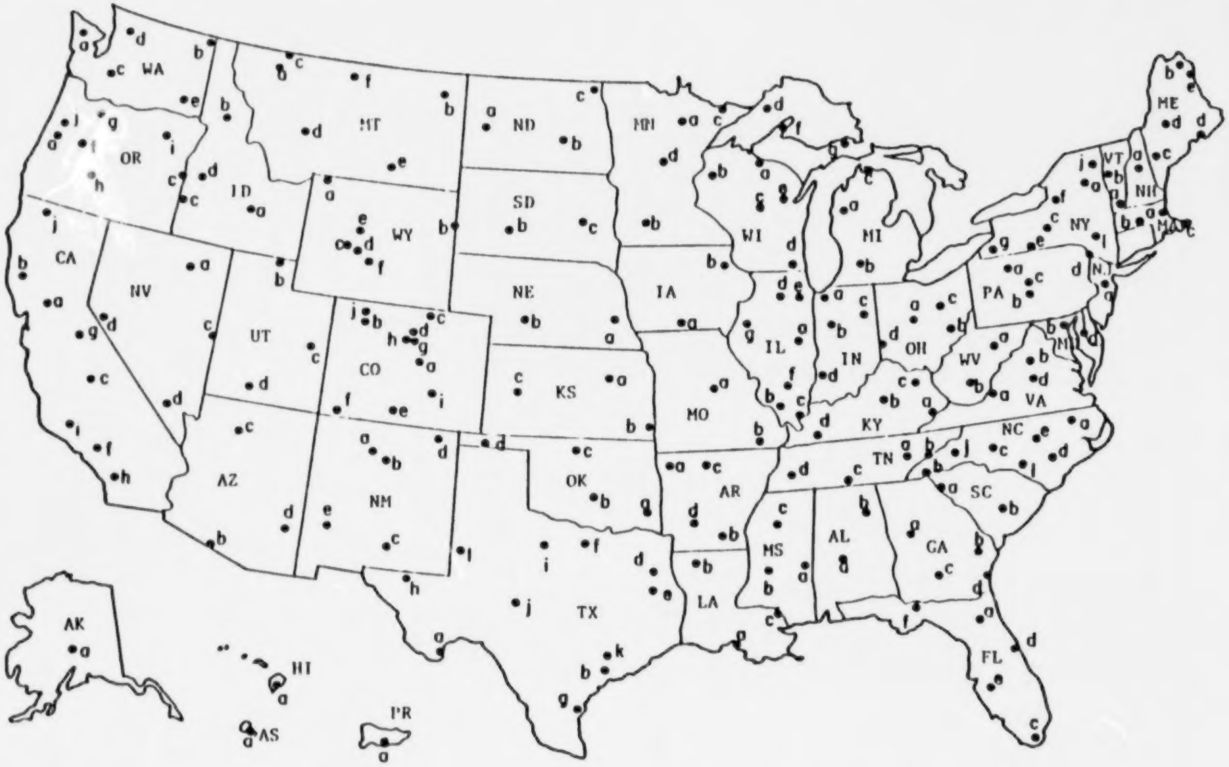


Figure L-1. This map indicates all sites that were active in the NADP/NTN monitoring network as of 11/15/85 (National Atmospheric Deposition Program, 1985).

Table L-3. Site operation dates, coordinates, and elevations for the combined EPRI and UAPSP networks. From Mueller et al., 1984.

Site No.	Site Location	Start Date	End Date	Latitude	Longitude	Elevation (m)
1	Montague, MA[a,b]	08/27/78	07/31/80	42°32'00"	72°32'08"	73
	Turner Falls, MA[a]	08/01/80	---	42°35'50"	72°32'55"	98
2	Scranton, PA[b,c]	08/25/78	12/31/80	41°34'30"	75°59'40"	335
	Tunkhannock, PA[c]	10/24/81	---	41°34'30"	75°59'40"	335
3	Indian River, DE[b]	08/29/78	06/30/80	38°34'50"	75°14'45"	6
4	Zanesville, OH[b,d]	08/20/78	---	39°59'02"	82°01'05"	250
5	Rockport, IN[b]	08/26/78	---	37°52'50"	87°07'47"	131
6	Giles County, TN[b]	08/24/78	06/30/80	35°17'05"	86°54'11"	244
7	Fort Wayne, IN[b,e]	08/18/78	---	41°02'39"	85°19'08"	244
8	Raleigh, NC[b]	09/08/78	---	35°43'43"	78°40'48"	128
9	Lewisburg, WV[b]	08/22/78	12/31/80	37°50'50"	80°25'00"	701
10	Gaylord, MI	11/07/81	---	44°56'58"	84°38'30"	473
11	Clearfield, KY	10/29/81	---	38°08'10"	83°27'17"	235
12	Alamo, TN	10/23/81	---	35°47'32"	90°08'03"	112
13	Winterport, ME	10/21/81	---	44°37'05"	68°58'30"	67
14	Uvalda, GA[f]	10/13/81	---	32°03'18"	82°28'25"	64
15	Selma, AL[g]	10/17/81	---	32°28'25"	87°05'03"	42
16	Clinton, MS	10/20/81	---	32°21'06"	90°17'15"	76
17	Marshall, TX	10/25/81	---	32°39'58"	94°25'06"	81
18	Lancaster, KS[h]	11/05/81	---	39°34'10"	95°18'17"	346
19	Brookings, SD[i]	10/30/81	---	44°19'43"	96°49'45"	499
20	Underhill, VT[f]	01/01/81	---	44°31'42"	72°52'08"	442
21	Big Moose, NY	10/26/81	---	43°49'03"	74°54'08"	603
22	McArthur, OH	10/01/81	05/15/84	39°14'06"	82°28'41"	224
23	Yampa, CO	08/12/82	---	40°10'	106°55'	2390

---

[a] Site 1 was moved from Montague to Turner Falls, MA.

[b] Co-located sampling conducted 1979. For later years, data are from only one of the two samplers.

[c] Site 2 operated through 12/31/80 as Scranton, PA. The same site was reactivated on 10/24/81 and the name was changed to Tunkhannock, PA.

[d] Site 4 was originally called Duncan Falls, OH.

[e] Site 7 was originally called Roanoke, IN.

[f] Co-located sampling being conducted from 10/09/83 for one year.

[g] Co-located sampling conducted from 10/17/81 to 01/21/83.

[h] Co-located sampling being conducted from 10/12/83 for one year.

[i] Co-located sampling conducted from 11/14/81 to 02/23/83.

The Multistate Atmospheric Power Production Pollution Study/Research in Acidity from Industrial Emissions (MAP3S/RAINE) wet deposition monitoring program began in 1976 with four sites (Whiteface, NY; Ithaca, NY; Penn State, PA; Charlottesville, Virginia); four additional sites (Champaign, IL; Brookhaven, NY; Lewes, DE; Oxford, OH) were added in 1978 and Oak Ridge National Laboratory joined the program in 1981. Precipitation samples are collected on a modified-event basis, as defined by the operator, and shipped cooled to a central laboratory where electrical conductivity, pH, SO_4^{2-}, NO_3^-, NH_4^+, Cl^-, Na^+, K^+, Ca^{2+}, and Mg^{2+} are measured. For additional information on data availability contact Dr. Tony Olsen, Battelle Pacific Northwest Laboratories, P.O. Box 999, Richland, Washington.

Other forms of wet deposition, such as clouds or fog have not been as extensively studied and no formal data bases have been developed. However, individual researchers have useful data for these sources of deposition. For example, as a part of the Cloud Chemistry Program, Dr. Volker Mohnen, Atmospheric Sciences Research Center, State University of New York at Albany, 1400 Washington Avenue, Albany, New York, has been characterizing the chemicals in cloud water. Similiarly, Dr. Michael R. Hoffman, Environmental Engineering Science, W. M. Keck, Engineering Laboratories, California Institute of Technology, Pasadena, California, has been studying the composition of fog water.

APPENDIX M

Supplementary Reports:

General Trends in Dry Deposition

Dry Deposition -- General Trends

Ozone

An indication of the increase in ozone concentration across the U.S. was given by Logan (1985) in her recent analysis of tropospheric ozone. The surface concentration has increased 0.006-0.022 ppm (20-100%) since the 1940s in both rural Europe and the central Eastern United States. An upward trend in annual mean ozone concentration in Germany is suggested by monitoring data from two sites in East Germany where increases of 5 to 12 ppb are reported from 1955 to 1975 (Ashmore et al., 1985). Seasonal patterns in ozone occurrence at the surface were discussed by Logan (1985): (1) a broad summer maximum within a few hundred kilometers of populated and industrialized regions of Europe and the U.S.; and (2) a minimum in summer or autumn in sparsely populated regions remote from industrial activity.

From hourly monitoring data, ozone has been characterized in the U.S. and Europe by a mean concentration over a selected time period (e.g., 7-hr, daily, weekly, monthly, annually). The most available example of this type characterization of the level of ozone across the U.S. is given by the estimation of the 7-hr seasonal mean (9 a.m.-4 p.m.; May-September) by kriging techniques using the SAROAD databases from 1978-1980 (Reagan, 1983). The ozone concentration is reported for one-half degree grid squares across the U.S.; an example of such a map is given in Figure M-1 for 1982. The mean seasonal ozone concentration is 0.035-0.056 ppm for the Eastern U.S. and this range is fairly characteristic for a large portion of the rest of the nation. Only few regions display concentrations higher than 56 ppb. These estimations were made without distinguishing among types of monitoring sites, but did not include sites within 10 km of large metropolitan centers. Investigating ozone air quality at remote sites located within National Forests ranging across the U.S. (Figure M-2), Evans et al. (1983a) reported the annual mean concentrations varied from site-to-site and year-to-year, but fell within the range of 0.025 to 0.050 ppm. Hourly ozone concentrations in excess of 0.120 ppm were occasionally observed. Such events were rare and generally noted during the spring and summer at sites in the Eastern U.S. prior to 1980. Similar annual mean ozone concentrations were reported for the 'clean air areas' of the Southern Black Forest (0.040-0.060 ppm) and the Bavarian Forest (0.030-0.050 ppm) in Germany (Blank, 1985). Seasonal and diurnal patterns of ozone at remote sites in the U.S. were reported by Evans et al. (1983a). The highest mean ozone concentrations occurred during the spring months (April-June), and the diurnal maxima occurred most frequently during the early afternoons (1300-1500 hr). A different seasonal pattern was reported from long-term monitoring in the Shenandoah National Park (Taylor and Norby, 1985). At this site, the 7-hr daylight mean ozone maxima occurred in June, July, and August. Monthly mean 7-hr daylight (1100-1800 hr) ozone in 1980 ranged from 0.02 to 0.06 ppm, and the peak 1-hr means never exceeded 0.10 ppm; concentration values quite similar to those reported by Evans et al. (1983a) at national forests across the country. Another indication of the trend in ozone concentration in the U.S. was reported by Lefohn et al. (1985) in a study of monitoring sites that were located within approximately 60 miles of a national forest east of the 95th meridian (Figure M-3). The authors reported, among other characterization information, the national forests that may experience a specified number of hourly occurrences

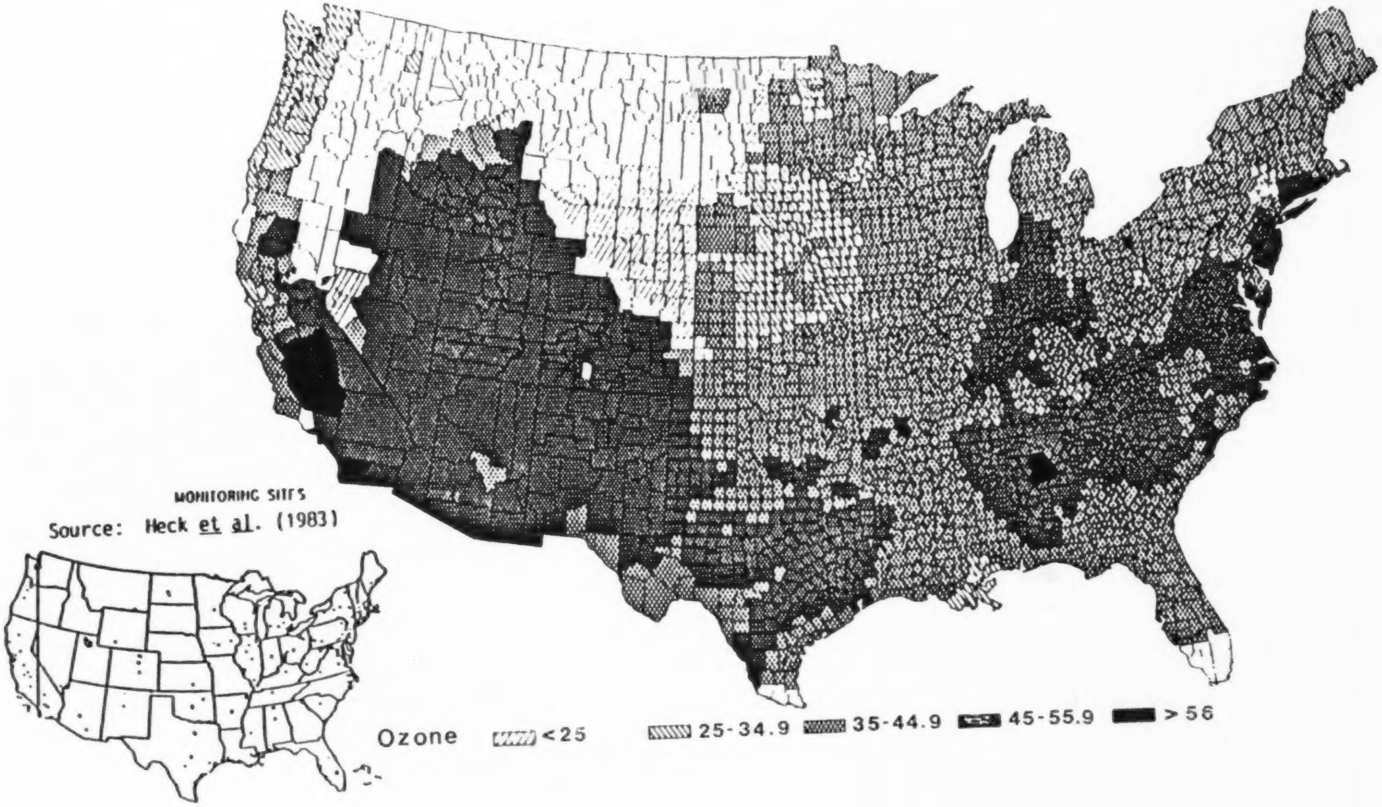


Figure M-1. Distribution of 7-hr (0900-1500 hr) seasonal mean ozone (ppb) for 1982 as estimated by the kriging techinque. Data from Reagan (1983). Map from R. J. Olsen, Oak Ridge National Laboratory (personal communication).

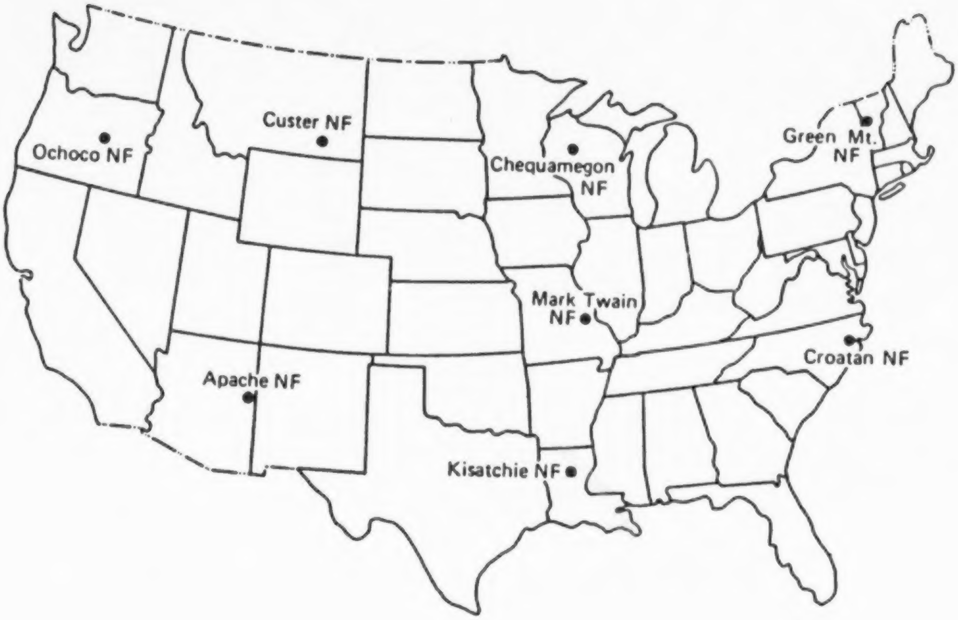
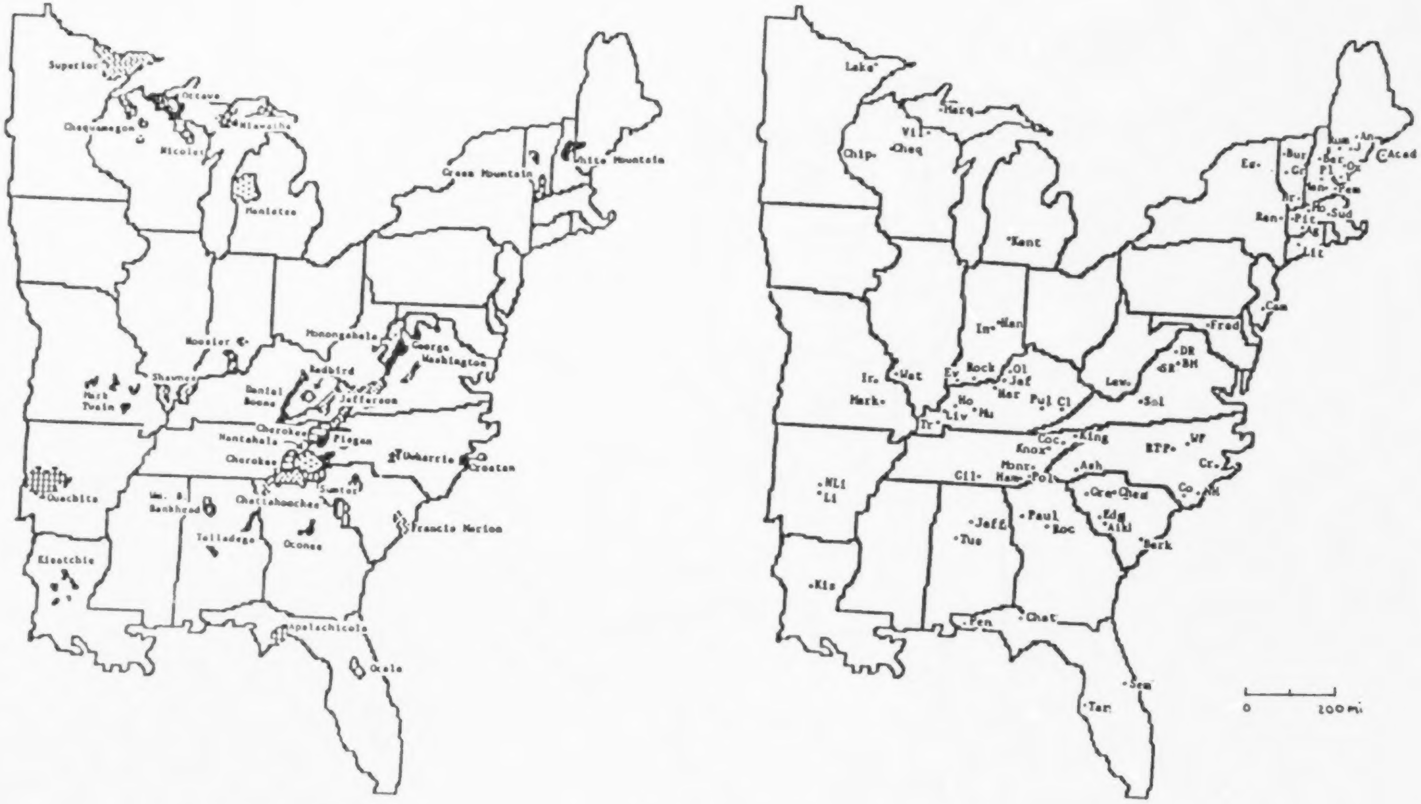


Figure M-2. Remote monitoring sites in National Forest areas of the U.S. From Evans (1985).



NATIONAL FORESTS

MONITORING SITES

Figure M-3. Location of monitoring sites used in estimation of air quality in National Forests east of the 95th meridian. From Lefohn et al. (1985).

equal to or greater than 0.10 ppm (Table M-1). If the air quality recorded at the site is actually representative of the air quality in the nearby national forest then this information is an indication of the ozone concentration for at least one if not all years during the period of 1978-1983, since not all sites are characterized for all years. The authors caution that before specific statements of risk are made, additional ozone monitoring is required at sites within the national forest and the distribution characterized.

Sulfur Dioxide

Over the past 10 to 15 years in the United States, SO_2 levels in urban areas and near many point sources have been markedly reduced by control programs (USEPA, 1982). The decreasing trend in urban concentration is shown in Figure M-4 with both annual means and values at the 90th percentile. The spatial and temporal trend in SO_2 concentration is best shown with range of maximums and values at the 90th percentile. These values are given in Figure M-4 for annual trends and also in Table M-2 for SO_2 concentrations by regions in the U.S. Regional differences are not striking, although the more industrialized and populated Regions I-V had annual mean concentration of 10 to 20 ppb, somewhat higher than the concentration range from the less industrialized, less populated Regions VI-X (3-15 ppb). These data also may reflect the location of the monitors, with some sited for population-oriented monitoring and others for point-source monitoring. The concentration of SO_2 is affected by meteorological variables influencing transport, dispersion, and removal, as well as by topography and location of source. As a result, the monitoring of SO_2 is obviously highly influenced by the site location. A better indication of regional differences in SO_2 concentrations may be differences in sulfur emission patterns (USEPA, 1982). Non-urban monitoring of SO_2 is more limited than urban monitoring. Annual mean concentrations of about 1 ppb are seen, with most values near the detectability level. Altshuller (1984), reviewing historical SO_2 concentrations, reported no apparent trend in non-urban monitoring from 1965 to 1977. An indication of seasonality of SO_2 occurrence in non-urban sites is given in the quarterly averaged SO_2 concentrations from six sites in the late '60s and early '70s shown in Table M-3. An annual average of about 5 ppb is observed with concentration highest in the first and fourth quarters. Rural sites in Kentucky, Ohio, and Indiana displayed a seasonality to SO_2 concentrations with means less than 5 ppb during summer and 15 to 20 ppb during winter. The annual mean concentrations in Europe are close to those observed in the U.S.; concentrations range from 10 ppb in rural areas of the United Kingdom, the Netherlands, and Federal Republic of Germany to 1 ppb or less in remote areas of northern and western Europe (Altshuller, 1984). Related to this observation, the emission rates in West Germany have remained at approximately 3.5 million metric tons/year between 1966 and 1978 (Guderian, 1985). In a study identifying monitoring sites that could be used to characterize air quality for potential impact on national forests, Lefohn et al. (1985) identified only 8 monitoring sites out of 33 possible that experienced SO_2 concentrations equal to or greater than 0.10 ppm more than 50 times over a 12-month period (Table M-4). Only one of these sites was in a national forest, the others were within 60 miles.

Table M-1. National Forests east of the 95th meridian potentially experiencing hourly ozone concentrations equal to or greater than the 0.10 ppm over the 7-month period April-October (1979-1983). From Lefohn *et al.* (1985).

Number of Occurrences ≥ 0.10 ppm			
< 50 Occurrences	50-100 Occurrences	100-200 Occurrences	> 200 Occurrences
Tombigee (MS)	Chattahoochee (GA)	Talladega (AL)	Hoosier (KY)
Apalachicola (FL)	Oconee (GA)	William B. Bankhead (AL)	
Ocala (FL)	Nantahala (NC)	Ouachita (AR)	
Shawnee (IL)	Cherokee (TN)	Uwharrie (NC)	
Daniel Boone (KY)		New Jersey Pine Barrens (Camden, NJ)	
Redbird (KY)			
Kisatchie (LA)			
Hiawatha (MI)			
Manistee (MI)			
Superior (MN)			
Mark Twain (MO)			
Pisgah (NC)			
Croatan (NC)			
White Mountain (NH)			
Francis Marion (SC)			
Sumter (SC)			
George Washington (VA)			
Jefferson (VA)			
Green Mountain (VT)			
Monongahela (WV)			
Chequamegon (WI)			
Nicolet (WI)			

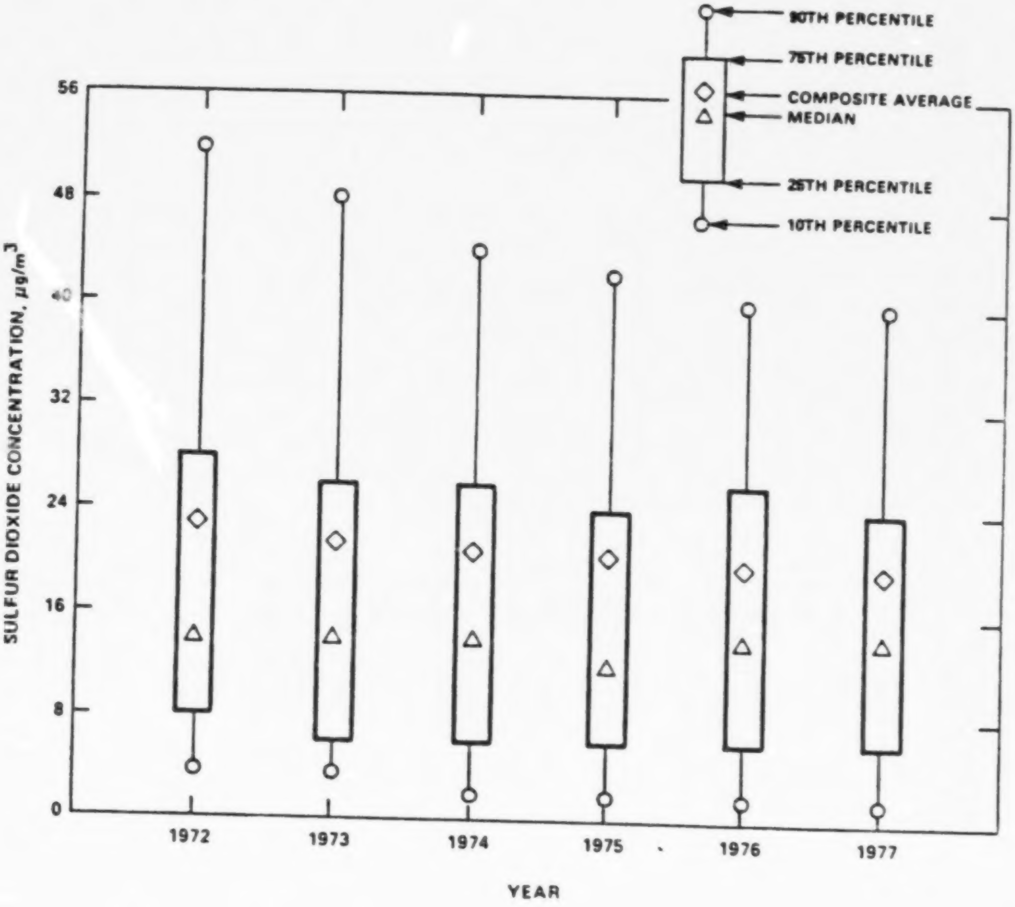


Figure M-4. Nationwide trends in annual average sulfur dioxide concentrations from 1972 to 1977 are shown for 1233 sampling sites (ug m^{-3} x (3.82 x 10^{-4}) = ppm SO_2). From EPA (1982).

Table M-2. Continuous SO_2 monitor results by region (ug m^{-3} x (3.82 10^{-4}) = ppm SO_2). From EPA (1982).

			Number of Observations Per Site				Arithmetic Mean				90th Percentile			
Region	Type	Number of Sites	Min.	Mean	Max.	S.D.	Min.	Mean	Max.	S.D.	Min.	Mean	Max.	S.D.
I	Valid	22	6665	7519	8416	567	16	33	59	12	34	65	147	27
	All	72	185	4582	8416	2720	8	39	138	23	14	77	340	52
II	Valid	51	6597	7540	8697	546	15	37	78	16	35	72	159	30
	All	87	140	5815	8697	2380	15	41	94	19	35	78	173	33
III	Valid	26	6578	7562	8638	670	12	51	140	23	34	97	282	46
	All	108	94	4381	8638	2534	7	45	140	21	14	86	282	40
IV	Valid	100	6678	8305	8755	574	5	23	63	12	9	54	135	27
	All	203	421	5754	8755	2848	3	23	77	13	3	49	180	29
V	Valid	111	6580	7640	8715	625	7	36	84	16	10	70	167	-30
	All	254	129	5512	8715	2327	3	37	192	25	5	73	501	50
VI	Valid	13	6631	7443	8452	607	3	13	31	7	3	31	69	19
	All	32	1669	5461	8452	2072	3	12	56	13	3	29	160	38
VII	Valid	13	6769	7540	8325	439	6	31	47	14	13	62	94	25
	All	38	334	4676	8325	2624	4	25	82	20	5	52	155	41
VIII	Valid	12	6741	7739	8624	514	3	40	152	47	3	100	488	146
	All	49	373	4694	8624	2358	3	34	152	39	3	89	488	113
IX	Valid	19	6857	7952	8638	507	3	8	29	6	3	16	48	12
	All	52	105	4973	8638	2525	3	24	87	20	3	49	213	49
X	Valid	18	6651	7854	8677	464	13	34	78	18	35	90	150	38
	All	29	625	6158	8677	2526	13	33	78	17	29	72	150	38

Table M-3. Sulfur dioxide concentrations at non-urban sites in the eastern United States (in ug m^{-3} x (3.82×10^{-4}) = ppm SO_2) (adapted from NASN data bank). From Altshuller (1984).

Site	First Quarter	Second Quarter	Third Quarter	Fourth Quarter	Annual Average
Acadia National Park, ME					
1968	8	7	5	9	10
1969	12	9	8	8	9
1970	15	7	8	15	11
1971	19	11	7	9	13
1972	6	6	6	7	7
1973	9	ND[a]	ND	ND	--
Coos County, NH					
1970	ND	ND	12	8	--
1971	12	10	7	9	9
1972	7	6	4	9	9
1973	13	ND	ND	ND	--
Calvert County, MD					
1970	ND	ND	10	18	--
1971	20	15	8	9	13
1972	5	6	6	9	7
1973	12	9	ND	8	--
Shenandoah National Park, VA					
1968	20	5	6	11	10
1969	16	7	9	11	11
1970	16	6	11	8	11
1971	15	8	7	10	11
1972	10	5	5	19	9
1973	18	8	6	7	9
Jefferson County, NY					
1970	ND	ND	16	ND	-
1971	8	5	6	7	7
1973	3	5	5	9	6
1973	8	19	ND	25	--
Monroe County, IND					
1967	19	5	6	33	11
1968	13	7	7	12	10
1969	19	10	8	18	14
1970	13	8	16	10	12
1971	11	8	7	14	11
1972	15	10	7	15	11
1973	30	11	10	10	15

[a] ND = not detectable.

Table M-4. National Forests east of the 95th meridian potentially experiencing hourly SO_2 concentrations equal to or greater than 0.10 ppm over the 7-month period April-October (1978-1983). From Lefohn *et al.* (1985).

Number of Hourly Occurrences $\geq$ 0.10 ppm	
50-100	> 100
Pensacola (FL)	Tarpon Springs (FL)
Jefferson Co. (KY)	Rockport (IN)
	Muhlenberg Co. (KY)
	Rumford (ME)
	Iron Co. (MO)
	Manchester (NH)

Nitrogen Dioxide

Nitrogen dioxide has been characterized by the EPA as annually averaged concentrations (USEPA, 1985). The EPA has used these levels, measured at 177 sites, to observe trends from 1975 to 1983. Like the other gaseous pollutant monitoring databases, long-term historical monitoring data for nitrogen dioxide (NO_2) and nitric oxide (NO) are generally not available for non-urban sites, but are available from a limited number of urban sites (Altshuller, 1984). The level of NO_2 in cities averaged about 0.026 ppm in 1983, essentially unchanged since 1975. Mean and maximum concentrations of NO_2 and NO for a number of rural sites are given in Table M-5. The mean NO_2 concentration ranged from 2.1 to 7.5 ppb and tended to exceed the mean concentrations of NO, although the NO maxima often exceed NO_2 maxima, suggesting localized intrusions of NO sources at many rural areas. Remote site monitoring reported even lower mean concentrations (Table M-6). Monitoring at Whiteface Mountain in 1983 reported averages of 1 ppb with excursions to 3 ppb (R. Bradow, personal communication).

Particulate

The character of particulate matter is dictated to some degree by size of the particle, ranging from 5×10^{-9} m to 10^{-4} m. The mass of suspended particles is usually estimated by filtration of known volumes of air and the dry weight determined. The accuracy and precision of particulate monitoring is limited by three considerations: (1) sampling methods; (2) sampling frequency; and (3) monitor location. These limitations are discussed in detail in the sulfur oxides criteria document (USEPA, 1982). From a general point of view however, the sampling method has limited determination of particulate chemistry, e.g., SOx and NOx concentration. The frequency of sampling removed the temporal element needed for characterization of this component for air quality as related to vegetational impacts. The location of the monitors obviously affects the concentrations reported and thus consideration of particular regions and potential impacts.

Only the sulfur and nitrogen components of particulate matter have been suggested to have any apparent influence on forest growth; however, it should be pointed out that very few studies have addressed this impact directly. Sulfate, along with ammonium ions, organics, carbon and combustion-associated metals, is a major component of fine particulate matter. Only a few studies of aerosol composition have actually conducted material balance or size fractionation. The spatial distribution of sulfate concentration east of the Mississippi, excluding the Northeast and South Atlantic states is shown in Figure M-5. The figure also indicates the seasonality of sulfate deposition with the area increasing during the summer months. Meteorological factors, influencing transport and conversion beyond the source, can expand the influence of SO_2 emissions. At non-urban sites in the Northeast and Midwest, sulfate concentrations during the summer increased during the 1960s, peaked in the early 1970s, and subsequently decreased (Altshuller, 1984). The seasonality of sulfate occurrence, specifically in rural sites, ranged from 1 ppb in the winter months to 4.6-5.7 ppb in summer (Altshuller, 1984). Diurnal patterns in concentration have been observed in studies of two rural sites (Kentucky and Virginia) during the summer of 1976 (Altshuller, 1984). Two types of patterns were observed, depending on the meteorological conditions.

Table M-5. Measurements of concentrations of nitrogen oxides at suburban and rural sites (ug m^{-3} x (5.32×10^{-4}) = ppm NO_2; x (8.15×10^{-4}) = ppm NO). From Altshuller (1984).

Site (Type)	Period of Measurement (Method)	Nitric Oxide (ug m^{-3})		Nitrogen Dioxide (ug m^{-3})	
		Mean	Max.	Mean	Max.
Montague, MA (R)[a]	Aug.-Dec. 1977 (chemilumin.)	3	78	7	73
Ipswich, MA (R)	Dec. 54-Jan. 55) (colorimetric)	ND	ND	2.6	3.8
Scranton, PA (S)	Aug.-Dec. 1977 (chemilumin.)	3	70	11	64
DuBois, PA (R)	June-Aug. 1974 (chemilumin.)	ND	ND	19	70
Bradford, PA (R)	July-Sep. 1975 (chemilumin.)	2.4	34	5.1	68
McHenry, MD (R)	June-Aug. 1974 (chemilumin.)	ND	ND	11	60
Indian River, DE (S)	Aug.-Dec. 1977 (chemilumin.)	3	114	5	48
Lewisburg, WV (R)	Aug.-Dec. 1977 (chemilumin.)	1	33	4	28
Shenandoah, VA (R)	July-Aug. 1980 (chemilumin.)	1	NA	4	NA
Research Triangle Park, NC (S)	Nov. 65-Jan. 66 Sep.66-Jan. 67 (colorimetric)	2.3 NA	NA NA	10.6 14.3	NA NA
Research Triangle Park, NC (S)	Aug.-Dec. 1977 (chemilumin.)	10	249	13	145
Green Knob, NC (R) Appalachian Mt.	Sep. 1965 (colorimetric)	2.7	NA	6.4	NA
Florida, southeast coast	July-Aug. 1954 (chemilumin.)	ND	ND	1.8	3.7

Table M-5 (continued)

Site (Type)	Period of Measurement (Method)	Nitric Oxide ($\mu g\ m^{-3}$)		Nitrogen Dioxide ($\mu g\ m^{-3}$)	
		Mean	Max.	Mean	Max.
DiRidder, LA (R)	June-Oct. 1975 (chemilumin.)	1.9	17	4.9	43
Wilmington, OH (S)	June-Aug. 1974 (chemilumin.)	ND	ND	13	90
McConnelsville, OH (R)	June-Aug. 1974 (chemilumin.)	ND	ND	12	70
Wooster, OH (S)	June-Aug. 1974 (chemilumin.)	ND	ND	13	90
New Carlisle, OH (R)	June-Aug. 1974 (chemilumin.)	6.0	64	27	NA
Ashland Co., OH (R)	May-Dec. 1980 (colorimetric)	4.3	NA	15.6	NA
Franklin Co., IN (R)	May-Dec. 1980 (chemilumin.)	3.0	NA	14.3	NA
Union Co., KY (R)	May-Dec. 1980 (chemilumin.)	2.5	NA	12.3	NA
Giles Co., TN (R)	Aug.-Dec. 1977 (chemilumin.)	5	96	11	55
Creston, IA (R)	June-Sep. 1975 (chemilumin.)	4.7	28	4.3	25
Wolf Point, MT (R)	June-Sep. 1975 (chemilumin.)	<1.0	NA	1.5	NA
Pierre, SD (R), site 40 km WNW of Pierre	July-Sep. 1978 (chemilumin.)	<0.25	NA	2.3	NA
Jetmore, KY (R)	Apr.-May 1978 (chemilumin.)	1.2	NA	7.5	NA

[a] R = rural. S = Suburban. ND = not determined. NA = not available.

Table M-6. Concentrations of nitrogen oxides measured at remote locations (ug m^{-3} x (5.32×10^{-4}) = ppm NO_2; x (8.15×10^{-4}) = ppm NO. From Altshuller (1984).

Site	Measurement Period (Method)	Concentrations in ug m^{-3} NO	NO_2	NO_x	Remarks
Colorado, USA Niwot Ridge	Jan. and April 1979 (chemilumin.)	0.02-0.06	NA	0.4-0.5	
Colorado, USA Niwot Ridge	Dec. 1980 to Jan. 1981 (chemilumin.)	NA	NA	< 0.1	
Colorado, USA Fritz Peak	Fall 1974; Summer Spring 1975-76 (absorption spectroscopy)	NA	< 0.02	NA	
	Dec. 1977 (chemilumin.)	NA	NA	0.2-0.5	
Island of Hawaii Mauna Kea	Nov. 1954 (colorimetric)	ND	2	ND	
Laramie, WY	Summer 1975 (chemilumin.)	0.01-0.06	NA	0.2-0.8	
Ireland, Adrigole Co. Cork	Aug.-Sept. 1974 (chemilumin.)	$\leq$ 0.02	0.8	NA	Maritime air
Ireland, Loop Head	April 1979 (Ciff. opt. abs. uv)	ND	0.3	ND	Maritime air
Ireland, Loop Head	June 1979 (chemilumin.)	< 0.01	0.16	NA	Maritime air

NA = Not available.
ND = Not determined.

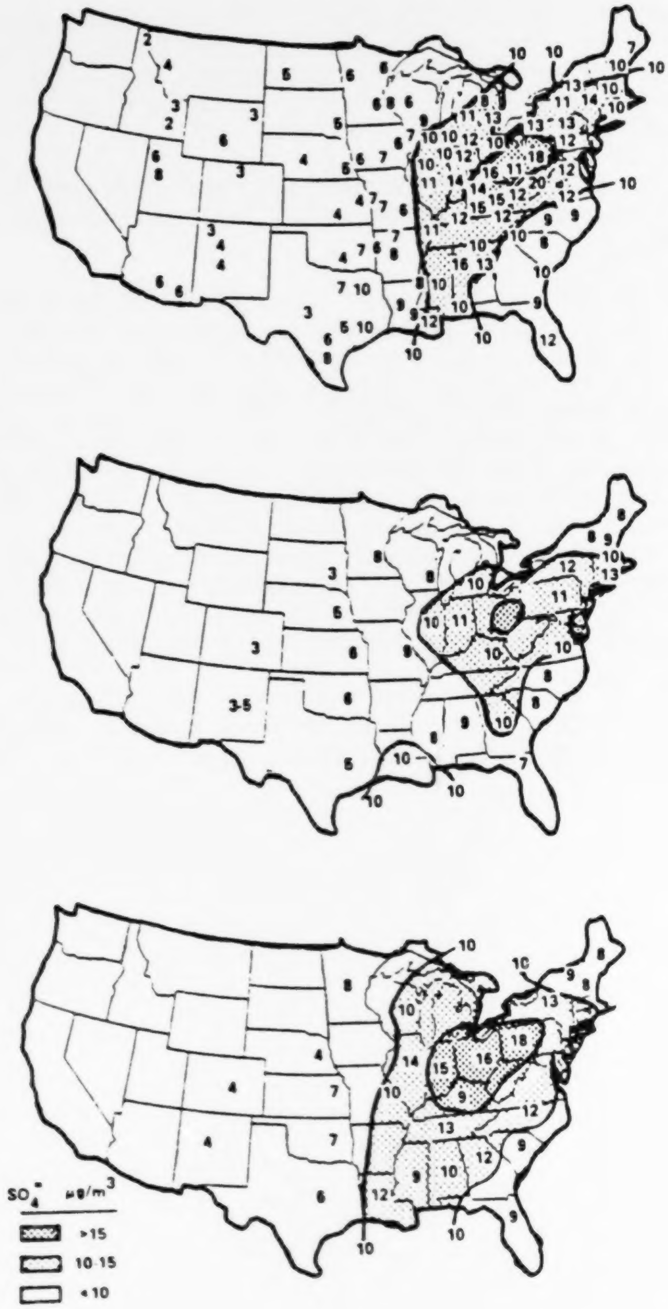


Figure M-5. Contour maps of sulfate concentrations for 1984 are shown: (a) annual average; (b) winter average; (c) summer average. From National Research Council (USEPA, 1984).

In one, the peak concentration occurred in mid-afternoon, about the same time as ozone peaked. The other pattern was characterized by peaks between 2000 and 0400 hours. This pattern was most pronounced on clear nights when ground fog developed. Neither pattern was observed after passage of a cold front when concentrations were very low.

Characterization of sulfate aerosol exposure is needed to define temporal and spatial distributions of concentrations for understanding and developing exposure regimes.

Nitrate is the other component of particulates of interest in discussing the ambient air quality as it relates to studies of dry deposition impact on forests. Most nitrates in the atmosphere are formed in gas-to-aerosol reactions, principally involving nitrogen dioxide and nitric oxide. These reactions may form HNO_3 (gas or aerosol), ammonium nitrate, sodium nitrate, and lesser compounds. Measurements of these components are subject to many errors. Sampling techniques have led to errors in determination of concentration levels (USEPA, 1982), consequently much of the data is not usable for exposure characterization. The air quality data regarding nitrate content are just not available for understanding the dynamics of occurrence over the year or even short-term temporal variations. At this time, developing sampling techniques and analysis should be the major effort to increase the understanding of nitrate aerosol, HNO_3, and other nitrogen components of particulate deposition.

The problems of dry particulate monitoring are not unique to nitrate aerosols. Anyone wishing a more complete understanding, as well as the current knowledge of particulate air quality, is referred to USEPA (1982); Altshuller (1984); Stensland (1984).

References

Abrahamsen, G., K. Bjor, and O. Teigen. 1977. Field experiments with simulated acid rain in forest ecosystems. I. Soil and vegetation characteristics, experimental design, and equipment. Research Report No. 4, 15 pp. SNSF-Project. NISH, 1432 Aas, NLK, Norway.

Adams, D. F. 1961. An air pollution phytotron. A controlled environment facility for studies into the effects of air pollutants on vegetation. J. Air Pollut. Contr. Assoc. 11:470-476.

Aiga, I., K. Omasa, and S. Matsumoto. 1984. Phytotrons in the National Institute for Environmental Studies. Res. Rep. Natl. Inst. Environ. Stud., Japan 66:133-154.

Altshuller, A. P. 1984. Atmospheric concentrations and distributions of chemical substances. In: A. P. Altshuller and R. A. Linthurst (eds.). The Acidic Deposition Phenomenon and Its Effects. Critical Assessment Review Papers. Volume I. Atmospheric Science. U.S. Environmental Protection Agency, Office of Research and Development, Washington, D.C. EPA-600/8-83-016BF. pp. 5-1 - 5-102.

Amiro, B. D., T. J. Gillespie, and G. W. Thurtell. 1984. Injury response of *Phaseolus vulgaris* to ozone flux density. Atmos. Environ. 18:1207-1215.

Appel, B. R., Y. Tokiwa, V. Povard, E. L. Kothny, and J. J. Weslowski. 1984. Determination of acidity in ambient air. Final Report to California Air Resources Board. Project A1-159-32. Sacramento.

Arndt, U. 1986. Proceedings of Open-Top Chamber Workshop. Environmental management in open-top chambers. Freiburg, Federal Republic of Germany. Commission of the European Communities.

Ashmore, M. R., J. N. B. Bell, and C. Dalpra. 1980. Visible injury to crop species by ozone in the United Kingdom. Environ. Pollut. (Series A) 21:209-215.

Ashmore, M. R., N. Bell, and J. Rutter. 1985. The role of ozone in forest damage in West Germany. Ambio 14:81-87.

Atkinson, C. J., W. E. Winner, and H. A. Mooney. 1986. A field portable exchange system for measuring carbon dioxide and water vapour exchange rates of leaves during fumigation with SO_2. Plant, Cell, and Environ. 9:711-719.

Austin, R. B., and P. C. Longden. 1967. A rapid method for the measurement of rates of photosynthesis using $^{14}CO_2$. Ann. Bot. 31:245-253.

Baker, C. K., M. H. Unsworth, and P. Greenwood. 1982. Leaf injury on wheat plants exposed in the field in winter to SO_2. Nature 299:149-151.

Banwart, W. L. 1985. Quality assurance plan for: Simulated acid rain effects on yield and growth of corn and soybeans and on soil parameters. Department of Agronomy, University of Illinois, Urbana, Illinois. 14 pp.

Battelle Pacific Northwest Laboratories. 1984. The toxic aerosol research facility at Battelle's Pacific Northwest Laboratories. Facility and Equipment. Battelle Pacific Northwest Laboratories. Richland, Washington. 20 pp.

Bennett, J. P., K. Barnes, and J. H. Shinn. 1980. Interactive effects of H_2S and O_3 on the yield of snap beans (Phaseolus vulgaris L.). Environ. Exp. Bot. 20:107-114.

Berry, C. R. 1970. A plant fumigation chamber suitable for forestry studies. Phytopathology 60:1613-1615.

Black, V. J., and M. H. Unsworth. 1979a. A system for measuring effects of sulphur dioxide on gas exchange of plants. J. Exp. Bot. 114:81-88.

Black, V. J., and M. H. Unsworth. 1979b. Effects of low concentrations of sulphur dioxide on net photosynthesis and dark respiration of Vicia faba. J. Exp. Bot. 30:473-483.

Blank, L. W. 1985. A new type of forest decline in Germany. Nature 314:311-314.

Bloom, A. J., H. A. Mooney, O. Bjorkman, and J. Berry. 1980. Materials and methods for carbon dioxide and water exchange analysis. Plant, Cell Environ. 3:371-376.

Brewer, R. F. 1978. The Effects of Present and Potential Air Pollution on Important San Joaquin Valley Crops: Sugar Beets. Final Report to California Air Resources Board. Project A6-161-30. Sacramento.

Brewer, R. F. 1979. The Effects of Present and Potential Air Pollution on San Joaquin Valley Cotton. Final Report to California Air Resources Board. Project A7-119-30. Sacramento.

Brewer, R. F. 1983. Effect of Ambient Air Pollutants on Thompson Seedless Grapes. Final Report to California Air Resources Board. Project A1-132-133. Sacramento.

Brewer, P. F., and A. S. Heagle. 1983. Interaction between Glomus geosporum and exposure of soybeans to ozone or simulated acid rain in the field. Phytopathology 73:1035-1040.

Buckenham, A. H., M. A. J. Parry, and C. P. Whittingham. 1982. Effects of aerial pollutants on the growth and yield of spring barley. Ann. Appl. Biol. 100:179-187.

Buckenham, A. H., M. A. Parry, C. P. Whittingham, and A. T. Young. 1981. An improved open-topped chamber for pollution studies on crop growth. Environ. Pollut. (Series B) 2:275-282.

Burmann, F. J., and K. A. Rehme. 1978. Instrumentation. In: W. W. Heck, S. V. Krupa, and S. N. Linzon (eds.). Handbook of Methodology for the Assessment of Air Pollution Effects on Vegetation, Air Pollution Control Association, Pittsburgh. pp. 2-1 to 2-24.

Cantwell, A. M. 1968. Effect of temperature on response of plants to ozone as conducted in a specially designed plant fumigation chamber. Plant Dis. Reptr. 52:957-960.

Carlson, R. W., F. A. Bazzaz, J. J. Stukel, and J. B. Wedding. 1976. Physiological effects, wind reentrainment, and rainwash of Pb aerosol particulate deposited on plant leaves. Environ. Sci. Technol. 10:1139-1142.

Chamberlain, A. C., and P. Little. 1981. Transport and capture of particles by vegetation. In: J. Grace, E. D. Ford, and P. G. Jarvis (eds.). Plants and Their Atmospheric Environment. Blackwell Scientific Publ., Oxford. pp. 147-173.

Chappelke, A. H., B. I. Chevone, and T. E. Burk. 1985. Growth response of yellow-poplar (*Liriodendron tulipfera* L.) seedlings to ozone, sulfur dioxide, and *simulated acidic precipitation*, alone and in combination. Environ. Exp. Bot. 25:233-244.

Chevone, B. I., Y. S. Yang, W. E. Winner, I. Storks-Colter, and S. J. Long. 1984. A rainfall simulator for laboratory use in acidic precipitation studies. J. Air Pollut. Contr. Assoc. 31:355-359.

Cogbill, C. V., and G. E. Likens. 1974. Acid precipitation in the Northeastern United States. Water Resources 10:33-37.

Colvill, K. E., R. M. Bell, T. M. Roberts, and A. D. Bradshaw. 1983. The use of open-top chambers to study the effects of air pollutants, in particular sulphur dioxide, on the growth of ryegrass *Lolium perenne* L. Part I. The long-term effect of filtering polluted *urban air or adding* SO_2 to rural air. Environ. Pollut. (Series A) 31:35-55.

Colvill, K. E., D. C. Horsman, M. L. Roose, T. M. Roberts, and A. D. Bradshaw. 1985. Field trials on the influence of air pollutants, and sulphur dioxide in particular, on the growth of ryegrass *Lolium perenne* L. Environ. Pollut. (Series A) 39:235-266.

Coyne, P. I., and G. E. Bingham. 1978. Photosynthesis and stomatal light responses in snap beans exposed to hydrogen sulfide and ozone. J. Air Pollut. Contr. Assoc. 28:1119-1123.

Coyne, P. I., and G. E. Bingham. 1981. Comparative ozone dose response of gas exchange in a ponderosa pine stand exposed to long-term fumigations. J. Air Pollut. Control Assoc. 31:38-41.

Darley, E. F., S. Lerman, and R. J. Oshima. 1968. Plant exposure chambers for dust studies. J. Air Pollut. Contr. Assoc. 18:28-29.

Davis, J. M., and H. H. Rogers. 1980. Wind tunnel testing of open-top field chambers for plant effects assessment. J. Air Pollut. Contr. Assoc. 30:905-907.

de Cormis, L., J. Bonte, and A. Tisne. 1975. Technique experimentale permettant l'etude de l'incidence sur la vegetation d'une pollution par le dioxyde de soufre appliquee en permanence et a dose subnecrotique. Pollut. Atmos. 66:103-107.

Evans, G. F., F. Finkelstein, B. Martin, and N. Possiel. 1983a. Ozone measurements from a network of remote sites. J. Air Pollut. Control Assoc. 33:291-296.

Evans, L. W., K. F. Lewin, M. J. Patti, and E. A. Cunningham. 1983b. Productivity of field-grown soybeans exposed to simulated acidic rain. New Phytol. 93:377-388.

Evans, L. S. 1984. Acidic precipitation effects on terrestrial vegetation. Ann. Rev. Phytopathol. 22:397-420.

Evans, L. S., G. S. Raynor, and D. M. A. Jones. 1984. Frequency distributions for duration and volumes of rainfalls in the eastern United States in relation to acidic precipitation. Water, Air, Soil Pollut. 23:187-195.

Farrar, J. F., J. Relton, and A. J. Rutter. 1977. Sulfur dioxide and the growth of Pinus sylvestris. J. Appl. Ecol. 14:861-875.

Fowler, D. 1986. Specifications of Open-Top Chambers Used in Barley Studies at the Institute of Terrestrial Ecology. Proceedings of European Open-Top Chamber Workshop. 1986. Commission of the European Communities. Freiberg, Federal Republic of Germany.

Fowler, David. 1980. Removal of sulphur and nitrogen compounds from the atmosphere in rain and by dry deposition. In: Proceedings of International Conference on Ecological Impact of Acid Precipitation. SNSF Project. Sandefjord, Norway. pp. 22-32.

Garsed, S. G., and A. J. Rutter. 1984. The effects of fluctuating concentrations of sulphur dioxide on the growth of Pinus sylvestris L. and Picea sitchensis (Bong.) Carr. New Phytol. 97:175-195.

Gmur, N. F., L. S. Evans, and K. F. Lewin. 1983a. Effects of ammonium sulfate aerosols on vegetation. I. Chamber design for long duration exposures. Atmos. Environ. 17:707-714.

Gmur, N. F., L. S. Evans, and K. F. Lewin. 1983b. Effects of ammonium sulfate aerosols on vegetation. II. Mode of entry and responses of vegetation. Atmos. Environ. 17:715-721.

Greenwood, P., A. Greenhalgh, C. Baker, and M. Unsworth. 1982. A computer controlled system for exposing field crops to gaseous air pollutants. Atmos. Environ. 16:2261-2266.

Guderian, R. 1977. Air Pollution. Phytotoxicity of Acidic Gases and Its Significance in Air Pollution Control. Ecol. Stud. 22. Springer-Verlag, New York.

Guderian, R. Ed. 1985. Air Pollution by Photochemical Oxidants. Formation, Transport, Control, and Effects on Plants. Ecol. Stud. 52. Springer-Verlag, New York.

Guderian, R., and H. Stratmann. 1962a. Freilandversuche zur Ermittlung von Schwefeldioxidwirkungen aur die Vegetation. Teil I. Ubersicht zur Versuchsmethodik und Versuchauswertung. Forschungsber. Landes Nordrhein-Westfalen Nr 1118 Westdeutscher Verlag, Koln Opladen.

Guderian, R., and H. Stratmann. 1962b. Freilandversuche zur Ermittlung von Schwefeldioxidwirkungen aur die Vegetation. Teil III. Grenzwerte schadlicher SO_2-Imissionen fur Obst- und Forstkulturen sowie fur landwirtschaftlikche und gartnerische Pflanzenarten. Forschungsber. Landes Nordrhein-Westfalen Nr 1118 Westdeutscher Verlag, Koln Opladen.

Hagar, S., and B. R. Kjondal. 1981. Decomposition of birch leaves: dry weight loss, chemical changes, and effects of artificial acid rain. Pedobiologia 22:232-245.

Hales, J. M. 1984. Precipitation scavenging processes. In: A. P. Altshuller and R. A. Linthurst (eds.), The Acidic Deposition Phenomenon and Its Effects: Critical Review papers. Volume 1. U.S. Environmental Protection Agency, Washington, D.C. EPA-600/8-83-016AF. pp. 1-80.

Halgren, J.-E., S. Linder, A. Richter, E. Troeng, and L. Granat. 1982. Uptake of SO_2 in shoots of Scots pine: field measurements of net flux of sulphur in relation to stomatal conductance. Plant, Cell, and Environ. 5:75-83.

Heagle, A. S., and R. B. Philbeck. 1978. Exposure techniques. In: W. W. Heck, S. V. Krupa, and S. N. Linzon (eds.). Handbook of Methodology for the Assessment of Air Pollution Effects on Vegetation, Air Pollutoin Control Association, Pittsburgh. pp. 6-1 - 6-19.

Heagle, A. S., and M. B. Letchworth. 1982. Relationships among injury, growth, and yield resposnes of soybean cultivars exposed to ozone at different light intensities. J. Environ. Qual. 11:690-694.

Heagle, A. S., D. E. Body, and E. K. Pounds. 1972. Effects of ozone on yield of sweet corn. Phytopathology 62:683-687.

Heagle, A. S., R. B. Philbeck, and W. W. Heck. 1973. An open-top chamber to assess the impact of air pollution on plants. J. Environ. Qual. 2:365-368.

Heagle, A. S., R. B. Philbeck, H. H. Rogers, and M. B. Letchworth. 1979. Dispensing and monitoring ozone in open-top field chambers for plant effects studies. Phytopathology 69:15-20

Heagle, A. S., R. B. Philbeck, R. F. Brewer, and R. E. Ferrel. 1983. Response of soybeans to simulated acid rain in the field. J. Environ. Qual. 12:538-543.

Heck, W. W., J. A. Dunning, and J. A. Hindawi. 1966. Ozone: nonlinear relation of dose and injury to plants. Science 151:511-515.

Heck, W. W., J. A. Dunning, and H. Johnson. 1968. Design of a simple plant exposure chamber. U.S. Dept. of Health, Educ., Welfre. National Center for Air Pollution Control. Publ. APDT-68-6. Cincinnati, Ohio.

Heck, W. W., R. B. Philbeck, and J. A. Dunning. 1978. A continuous stirred tank reactor (CSTR) system for exposing plants to gaseous air contaminants. Principles, specifications, construction, and operation. Agric. Res. Serv. U.S. Dept. Agric. ARS-S-181. New Orleans, Louisiana.

Heck, W. W., W. J. Clore, I. A. Leone, D. P. Ormrod, R. M. Pool, and O. C. Taylor. 1985. Multi-Year Research Plan for the Lake Erie Generating Station (LEGS) Grape Study. Vol. II -- Technical Report. State Board on Electrical Generating, Siting, and the Environment, New York Department of Public Service, Albany.

Heck, W. W., O. C. Taylor, R. Adams, G. Bingham, J. Miller, E. Preston, and L. H. Weinstein. 1982. Assessment of crop loss from ozone. J. Air Pollut. Contr. Assoc. 32:353-361.

Heck, W. W., W. W. Cure, J. O. Rawlings, L. J. Zaragoza, A. S. Heagle, H. E. Heggestad, R. J. Kohut, L. W. Kress, and P. J. Temple. 1984. Assessing impacts of ozone on agricultural crops: I. Overview. J. Air Pollut. Contr. Assoc. 34:729-735.

Heggestad, H. E. T. J. Gish, E. H. Lee, J. H. Bennett, and L. W. Douglass. 1985. Interaction of soil moisture stress and ambient ozone on growth and yields of soybeans. Phytopathology 75:472-477.

Heggestad, H. E., R. K. Howell, and J. H. Bennett. 1977. The Effects of Oxidant Air Pollutants on Soybeans, Snap Beans, and Potatoes. U.S. Environmental Protection Agency, Corvallis, Oregon. EPA-600/3-77-128.

Hill, A. C. 1967. A special purpose plant environmental chambr for air pollution studies. J. Air Pollut. Contr. Assoc. 17:743-748.

Hill, A. C., L. G. Transtrum, M. R. Pack, and A. Holloman, Jr. 1959. Facilities and techniques for maintaining a controlled fluoride environment in vegetation studies. J. Air Pollut. Contr. Assoc. 9:22-27.

Hoffman, W. A., Jr., S. E. Lindberg, and R. R. Turner. 1980. Precipitation acidity: The role of the forest canopy in acid exchange. J. Environ. Qual. 9:95-100.

Hogsett, W. E., D. T. Tingey, and S. R. Holman. 1985. A programmable exposure control system for determination of the effects of pollutant exposure regimes on plant growth. Atmos. Environ. 19:1135-1145.

Irving, P. M. 1983. Acidic precipitation effects on crops: a review and analysis of research. J. Environ. Qual. 12:442-453.

Irving, P. M. 1985. Modeling the response of greenhouse-grown radish plants to acidic rain. Environ. Exp. Bot. 25:327-338.

Irving, P. M. 1985. Biochemical transformations in two plant/soil systems exposed to simulated acidic precipitation. In: Proceedings of the Seventh International Symposium on Environmental Biogeochemistry. Rome, Italy.

Irving, P. M., and J. E. Miller. 1981. Productivity of field-grown soybeans exposed to acid rain and sulfur dioxide alone and in combination. J. Environ. Qual. 10:473-478.

Irving, P. M., and J. E. Miller. 1984. Synergistic effect on field-grown soybeans from combinations of sulfur dioxide and nitrogen dioxide. Can. J. Bot. 62:840-846.

Jacobson, J. S., and J. M. McManus. 1985. Patterns of atmospheric sulfur dioxide occurrence: An important criterion in vegetation effects assessment. Atmos. Environ. 19:501-506.

Jacobson, J. S., J. Troiano, and L. Heller. 1985. Stage of development responses, and recovery of radish plants from episodic exposure to simulated acidic rain. J. Exp. Bot. 36:159-167.

Jensen, K. F., and F. W. Bender. 1977. Seedling-size fumigation chambers. Forest Service Research Paper NE-383. Northeast For. Exp. Sta. Upper Darby, Pa. 4 pp.

Johnston, J. W., D. W. Shriner, and C. H. Abner. 1986. Design and performance of the exposure system for measuring the response of crops to aicd rain and gaseous pollutants in the field. J. Air Pollut. Contr. Assoc. 36:894-899.

Johnston, J. W., D. S. Shriner, C. I. Klarer, and D. M. Lodge. 1982. Effects of rian pH on senescence, growth, and yield of bush bean. Environ. Exp. Bot. 22:329-337.

Jones, T., and T. A. Mansfield. 1982. The effect of SO_2 on growth and development of Phleum pratense under different light and temperature regimes. Environ. Pollut. (Series A) 25:57-71.

Jones, H. C., N. L. Lacasse, W. S. Liggett, and F. Weatherford. 1977. Experimental air exclusion system for field studies of SO_2 effects on crop productivity. U.S. Environmental Protection Agency. Washington, D.C. EPA-600/7-77-122.

Karlsson, S., and B. Sveinbjornson. 1981. Methodological comparison of photosynthetic rates measured by the $^{14}CO_2$ technique or infrared gas analysis. Photosynthetica 15:447-452.

Kats, G., C. R. Thompson, and W. C. Kuby. 1976. Improved ventilation of open-top greenhouses. J. Air Pollut. Contr. Assoc. 26:1089-1090.

Kats, G., D. M. Olszyk, and C. R. Thompson. 1985. Open-top experimental chambers for trees. J. Air Pollut. Contr. Assoc. 12:1298-1301.

Keller, T. 1976. Auswirkungen niedriger SO_2-Konzentrationen auf junge Fichten. Schweiz. Zeit. Forstwes. 127:237-251.

Keller, T., and R. Hasler. 1984. The influence of a fall fumigation with ozone on the stomatal behavior of spruce and fir. Oecologia (Berlin) 64:284-286.

Kelly, J. M., and R. C. Strickland. 1984. CO_2 efflux from deciduous forest litter and soil in response to simulated acid rain treatment. Water, Air, Soil Pollut. 23:431-440.

Kelly, J. M., R. C. Strickland, F. P. Weatherford, and J. C. Noggle. 1984. Evaluation of simulated acid precipitation effects on forest microcosm. Final Report to the Electric Power Research Institute, RP-1632. EPRI EA-3500. Palo Alto, California.

Killham K., M. K. Firestone, and J. G. McColl. 1983. Acid rain and soil microbial activity: Effects and their mechanism. J. Environ. Qual. 12:133-137.

Kimmerer, T. W., and T. T. Kozlowski. 1981. Stomatal conductance and sulfur uptake of five clones of *Populus tremuloides* exposed to sulfur dioxide. Plant. Physiol. 67:990-995.

Kohut, R., and J. A. Laurence. 1983. Yield response of red kidney bean *Phaseolus vulgaris* to incremental ozone concentrations in the field. Environ. Pollut. (Series A) 32:233-240.

Korner, C. H., J. A. Scheel, and H. Bauer. 1979. Maximum leaf diffusive conductance in vascular plants. Photosynthetica 13:45-82.

Krause, G. H. M., and H. Kaiser. 1977. Plant responses to heavy metals and sulphur dioxide. Environ. Pollut. 12:63-71.

Krause, G. H. M., B. Prinz, and K. D. Jung. 1984. Forest effects in West Germany. In: D. D. Davis, A. A. Millen, and L. Dochinger (eds.). Symposium on Air Pollution and the Productivity of the Forest. Izaak Walton League of America, Arlington, Virginia. pp. 297-332.

Kress, L. W., and J. E. Miller. 1983. Impact of ozone on soybean yield. J. Environ. Qual. 12:276-281.

Krizek, D. T., and J. C. McFarlane. 1983. Controlled-environment guidelines. HortScience 18:662-664.

Kuja, A., R. Jones, and A. Enyedi. 1986. A mobile rain exclusion canopy and gaseous pollutant reduction system to determine dose-response relationships between simulated acid precipitation and yield of field grown crops. Water, Air, and Soil Pollut. 31:307-315.

Lane, P. I., and J. N. B. Bell. 1984a. The effects of simulated urban air pollution on grass yield: Part I -- Description and simulation of ambient pollution. Environ. Pollut. (Series B) 8:245-263.

Lane, P. I., and J. N. B. Bell. 1984b. The effects of simulated urban air pollution on grass yield: Part 2 -- Performance of *Lolium perenne*, *Phleum pratense*, and *Dactylis glomerata* fumigated with SO_2, NO_2, and/or NO. Environ. Pollut. (Series A) 35:97-124.

Lange, O. L., and J. D. Tenhunen. 1984. A minicuvette system for measurement of CO_2 exchange and transpiration of plants under controlled conditions in field and laboratory. Pub. Heinz Walz, MeB-und Regeltechnic, D-8521 Effeltrich, West Germany. 11 pp.

Lange, O. L., and J. D. Tenhunen. 1985. CO_2/H_2O porometer for the measurement of CO_2 gas exchange and transpiration of plants under natural conditions. Pub. Heinz. Waltz, MeB-und Regeltechnic, D-8521 Effeltrich, West Germany. 13 pp.

Larcher, W. 1980. Physiological Plant Ecology. Springer-Verlag, New York. 2nd Edition.

Lauenroth, W. K., D. G. Milchunas, and J. L. Dodd. 1983. Response of a grassland to sulfur dioxide and nitrogen additions under controlled SO_2 exposure. Environ. Exp. Bot. 23:339-346.

Laurence, J. A., D. C. MacLean, R. H. Mandl, R. E. Schneider, and K. W. Hansen. 1982. Field tests of a linear gradient system for exposure of row crops to SO_2 and HF. Water, Air, Soil Pollut. 17:399-407.

Laurence, J. A., and R. J. Kohut. 1984. Lake Erie Generating Station Grape Study. Phase I and II. Contract #GF 127.1T123083. Niagara Mohawk Power Company of the New York State Public Service Commission, Albany.

Lauver, T. L., and D. C. McCune. 1985. Kinetics of removal of particulate deposits from foliage by precipitation. In: J. S. Jacobson and L. S. Raymond, Jr. (eds.). Proceedings of the Second New York State Symposium on Atmospheric Deposition. Center for Environmental Research, Cornell University, Ithaca, New York. pp. 83-89.

Lee, J. J., and R. A. Lewis. 1976. Field experimental component. In: R. A. Lewis and A. S. Lefohn (eds.). The Bioenvironmental Impact of a Coal-Fired Power Plant. First Interim Report, Colstrip, Montana -- December 1974, U.S. Environmental Protection Agency, Corvallis, Oregon. EPA-600/3-76-002. pp. 95-101.

Lee, J. J., and D. E. Weber. 1979. The effect of simulated acid rain on seedling emergence and growth of eleven woody species. Forest Sci. 25:393-398.

Lee, J. J., R. A. Lewis, and D. E. Body. 1975. A field experimental system for the evaluation of the bioenvironmental effect of sulfur dioxide. In: D. Wilson and F. Clark (eds.). Proceedings of the Fort Union Coal Field Symposium. pp. 608-620. Volume 5, Montana Academy of Science, Billings, Montana.

Lee, J. J., G. E. Neely, S. C. Perrigan, and L. C. Grothaus. 1981. Effect of simulated sulfuric acid rain on yield, growth, and foliar injury of several crops. Environ. Exp. Bot. 21:171-185.

Lefohn, A. S. and H. M. Benedict. 1983. The potential for the interaction of acidic precipitation and ozone pollutant doses affecting agricultural crops. In: Proceedings of the 76th Annual Meeting of the Air Pollution Control Association, Atlanta, June 19-24, 1983.

Lefohn, A. S., and H. M. Benedict. 1985. Exposure considerations associated with characterizing ozone ambient air quality monitoring data. In: Si-Duck Lee (ed.). Evaluation of the Scientific Basis for Ozone/Oxidants Standards. Air Pollution Control Association, Pittsburgh. pp. 17-31.

Lefohn, A. S., and S. V. Krupa. 1984. Sulfate as a surrogate for hydrogen in rainfall -- an analysis of rainfall chemistry data. Prepared for the U.S. Environmental Protection Agency. Washington, D.C.

Lefohn, A. S., and D. T. Tingey. 1984. Co-occurrence of potentially phytotoxic concentrations of various gaseous air pollutants. Atmos. Environ. 18:2521-2526.

Lefohn, A. S., C. E. Davis, and J. M. Benedict. 1985. The characterization of ozone and sulfur dioxide exposures near some United States National Forests. Prepared for the American Petroleum Institute, Washington, D.C.

Lefohn, A. S., W. E. Hogsett, and D. T. Tingey. 1986a. A method for developing ozone exposures that mimic ambient conditions in agricultural areas. Atmos. Environ. 20:361-366.

Lefohn, A. S., W. E. Hogsett, and D. T. Tingey. 1986b. The development of sulfur dioxide and ozone exposure profiles that mimic ambient conditions in the rural southeastern United States. Atmos. Environ. In press.

Lefohn, A. S., C. E. Davis, D. T. Tingey, and W. E. Hogsett. 1986c. Co-occurrence patterns of gaseous air pollutant pairs at different minimum concentrations in the United States. Atmos. Environ. In press.

Legge, A. H., D. R. Jacques, R. G. Amundson, and R. B. Walker. 1977. Field studies of pine, spruce, and aspen periodically subjected to sulfur gas emissions. Water, Air, Soil Pollut. 8:105-129.

Lewin, K. F., and L. S. Evans. 1984. Design of an experimental system to determine the effects of rainfall acidity on vegetation. Brookhaven National Laboratory Report No. 34649. Upton, New York. 15 pp.

Lindberg, S. E., and S. B. McLaughlin. 1986. Air pollution interactions with vegetation: Research needs in data acquisition and interpretation. In: S. V. Krupa and A. H. Legge (eds.) Air Pollutants and Their Effects on Terrestrial Ecosystems. John Wiley and Sons, New York. In press.

Lindberg, S. E., R. C. Turner, N. M. Ferguson, and D. Matt. 1977. Walker Branch watershed element cycling studies: Collection and analysis of wetfall for trace elements and sulfate. In: D. L. Correl (ed.) Watershed Research in Eastern North America: A Workshop to Compile Results. Volume 1. Chesapeake Bay Center for Environmental Studies, Smithsonian Institute, Edgewater, Maryland. pp. 125-150.

Linder, S., B. Nordstrom, J. Parsby, E. Sundbom, and E. Troeng. 1980. A gas exchange system for field measurements of photosynthesis and transpiration in a 20-year-old stand of Scots pine. Tech. Rep., Swedish Agric. Univ. Uppsala, Sweden. 34 pp.

Lockyer, D. R., D. W. Cowling, and L. H. P. Jones. 1976. A system for exposing plants to atmospheres containing low concentrations of sulphur dioxide. J. Exp. Bot. 27:397-409.

Logan, J. A. 1985. Tropospheric ozone: seasonal behavior, trends, and anthropogenic influence. J. Geophys. Res. 90:10,463-10,481.

Lovett, G. M. 1984. Dates and mechanisms of cloud water deposition to a subalpine balsam fir forest. Atmos. Environ. 18:361-371.

Lovett, G. M. W. A. Reiners, and R. K. Olson. 1982. Cloud droplet deposition in subalpine balsam fir forests: Hydrologic and chemical inputs. Science 218:1303-1304.

Magnuson, C. E., Y. Fares, J. D. Goesch, C. E. Nelson, B. R. Strain, C. H. Jaeger, and E. G. Bilpush. 1982. An integrated tracer kinetics system for studying carbon allocation on plants using continuously produced $^{11}CO_2$. Radiat. Environ. Biophys. 2:51-65.

Mahon, J. D., and J. Domey. 1979. A light-weight battery operated infrared gas analyzer for field measurements of photosynthetic CO_2 exchange. Photosynthetica 13:459-466.

Male, L. M. 1982. An experimental method for predicting plant yield response to pollution time series. Atmos. Environ. 16:2247-2252.

Male, L. M., E. Preston, and G. Neely. 1983. Yield response curves of crops exposed to SO_2. Atmos. Environ. 17:1589-1593.

Mandl, R. H., J. A. Laurence, and R. J. Kohut. 1987. Development and testing of new open-top chambers for exposing large perennial plants to air pollutants in the field. Phytopathology. In press.

Mandl, R. H., L. H. Weinstein, D. C. McCune, and M. Keveny. 1973. A cylindrical open-top field chamber for exposure of plants to air pollutants in the field. J. Environ. Qual. 2:371-376.

Marple, V. A., and K. L. Rubow. 1983. An aerosol chamber for instrument evaluation and calibration. Amer. Ind. Hyg. Assoc. J. 44:361-367.

Matsushima, J., and R. F. Brewer. 1972. Influence of sulfur dioxide and hydrogen fluoride as a mix or reciprocal exposure on citrus growth and development. J. Air Pollut. Contr. Assoc. 22:710-713.

McColl, J. G., and R. Johnson. 1983. Effects of simulated acid rain on germination and early growth of Douglas fir and ponderosa pine. Plant Soil 74:125-129.

McCune, D. C., D. C. MacLean, and R. E. Schneider. 1976. Experimental approaches to the effects of airborne fluoride on plants. In: T. A. Mansfield (ed.) Effects of Air Pollutants on Plants. Society for Experimental Biology Seminar Series, Vol. 1. Cambridge University Press, Massachusetts. pp. 31-46.

McCune, D. C., D. H. Silberman, R. H. Mandl, L. H. Weinstein, P. C. Freudenthal, and P. A. Giardina. 1977. Studies on the effects of saline aerosols of cooling tower origin on plants. J. Air Pollut. Control Assoc. 27:319-324.

McLaughlin, S. B., V. J. Schorn, and H. C. Jones. 1976. A programmable exposure system for kinetic dose-response studies with air pollutants. J. Air Pollut. Contr. Assoc. 26:132-135.

McLaughlin, S. B., D. S. Shriner, R. K. McCorathy, and L. K. Mann. 1979. The frequency of SO_2 dosage kinetics and exposure frequency on photosynthesis and transpiration of kidney beans (Phaseolus vulgaris L.). Environ. and Exp. Bot. 19:179-191.

McLaughlin, S. B., R. K. McConathy, D. Duvick, and L. K. Mann. 1982. Effects of chronic air pollution stress on photosynthesis, carbon allocation, and growth of white pine trees. Forest Sci. 28:60-70.

McLeod, A. R., K. Alexander, and P. Hatcher. 1983. A Prototype System for Open-Air Fumigation of Agricultural Crops. 2. Construction and Description. Central Electricity Generating Board. Technology Planning and Research Division. Report TPRD/L/2475/N83. Leatherhead, United Kingdom.

McLeod, A. R., J. E. Fackrell, and K. Alexander. 1985. Open-air fumigation of field crops: Criteria and design for a new experimental system. Atmos. Environ. 19:1639-1649.

Menser, H. A., and H. E. Heggestad. 1964. A facility for ozone fumigation of plant materials. Crop Sci. 4:103-105.

Miller, J. E., W. Prepejchal, and H. J. Smith. 1981. Relative sensitivity of field corn hybrids to ozone: A field study. Report No. ANL-81-85-III. Argonne National Laboratory, Illinois. pp. 30-36.

Miller, J. E., D. G. Sprugel, H. J. Smith, and P. B. Xerikos. 1980. Open-air fumigation system for investigation of sulfur dioxide effects on crops. Phytopathology 70:1124-1128.

Miller, P. R., and R. M. Yoshiyama. 1973. Self-ventilated chambers for identification of oxidant damage to vegetation at remote sites. Environ. Sci. Tech. 7:66-68.

Mooi, J. 1972. Onderzoek naar gevoeligheid van houtige gewassen voor SO_2 en HF. (Investigation on the sensitivity of trees and shrubs to air pollution). Inst. Phytopath. Res. Wag. Ann. Rep. 1971, pp. 169-173, 195.

Mooney, H. A. 1972a. The carbon balanace of plants. Ann. Rev. Syst. Ecol. 3:315-346.

Mooney, H. A. 1972b. Carbon dioxide exchange of plants in natural environments. Bot. Rev. 38:455-469.

Morison, J. I. L., and R. M. Gifford. 1984. Ethylene contamination of CO_2 cylinders. Plant Physiol. 75:275-277.

Moser, T. J., T. H. Nash, and W. D. Clark. 1980. Effects of long-term field sulfur dioxide fumigation on Arctic carbou forage lichens. Can. J. Bot. 58:2235-2240.

Mueller, P. W., and S. G. Garsed. 1984. A microprocessor-controlled system for exposing plants to fluctuating concentrations of sulphur dioxide. New Phytol. 97:165-173.

Mueller, P. K., J. J. Jansen, and M. A. Allen. 1984. Utility and precipitation study. Second Summary Report. Utility Acid Precipitation Study Program. UAPS109. Edison Electric Institute. Washington, D.C.

Musselman, R. C., R. J. Oshima, and R. E. Gallavan. 1983. Significance of pollutant concentration distribution in the response of "red kidney" beans to ozone. J. Amer. Soc. Hort. Sci. 108(2):347-351.

Musselman, R. C., J. L. Sterrett, and A. L. Granett. 1985. A portable fogging apparatus for field or greenhouse use. HortScience 20:1127-1129.

Musselman, R. C., P. M. McCool, R. J. Oshima, and R. R. Teso. 1986. Field chambers for assessing crop loss from air pollutants. J. Environ. Qual. 15:152-157.

National Atmospheric Deposition Program. 1985. NADP/NTN Report: Precipitation Chemistry; Third Quarter 1983. Natural Resource Ecology Laboratory, Colorado State University, Fort Collins. 258 pp.

Nilsen, E. T., M. R. Sharife, and P. W. Rundel. 1984. Comparative water relations of phraetophytes in the Sonoran Desert of California. Ecology 63:767-778.

Noble, R. D., and K. F. Jensen. 1983. An apparatus for monitoring CO_2 exchange rates in plants during SO_2 and O_3 fumigation. J. Expt. Bot. 34:470-475.

Norby, R. J., and T. T. Kozlowski. 1981. Relative sensitivity of wood plants to SO_2 at high or low exposure temperature. Oecologia 51:33-36.

Norby, R. J., and T. T. Kozlowski. 1982. The role of stomata in sensitivity of Betula papyrifera seedlings to SO_2 at different humidities. Oecologia 53:34-39.

Norby, R. J., and R. J. Luxmoore. 1983. Growth analysis of soybean exposed to simulated acid rain and gaseous air pollutants. New Phytol. 95:277-287.

Norby, R. J., B. K. Takemoto, J. W. Johnston, and D. S. Shriner. 1986. Acetylene reduction rate as a physiological indicator of the response of field-grown soybeans to simulated acid rain and ambient gaseous pollutants. Environ. Exper. Bot. 26(3):285-290.

Northrop Services, Inc. 1983. Work Assignment 5. Air quality related values. Air pollution fumigation studies, No. 1. SP4162-83-08. Research Triangle Park, North Carolina. 34 pp.

Nystrom, S. D., R. C. Hendrickson, G. C. Pratt, and S. V. Krupa. 1982. A computerized open-top field chamber system for exposing plants to air pollutants. Agri. Environ. 7:213-221.

Oechel, W., and W. T. Lawrence. 1979. Energy utilization and carbon metabolism in Mediterranean scrub vegetation of Chile and California. I. Methods: a transportable cuvette field photosynthesis and data acquisition system and representative results for Ceanothus greggii. Oecologia 39:321-335.

Ogner, G., and O. Teigen. 1980. Effects of acid irrigation and liming on two clones of Norway spruce. Plant Soil 57:305-321.

Oliva, M., and L. Steubing. 1976. Effects of H_2S fumigation on the photosynthesis, respiration, and water budget of Spinacea oleracea. Angew Botanik 50:1-17.

Olsen, A. R., and C. R. Watson. 1984. Acid precipitation in North America: 1980, 1981, and 1982 annual data summaries based on acid deposition system data base. EPA-600/7-84-097. National Technical Information Service, Springfield, Virginia. PB 85 162 447/AS.

Olszyk, D. M., and T. W. Tibbits. 1981. Stomatal response and leaf injury of Pinus sativus L. with SO_2 and O_3 exposures. Plant Physiol. 67:539-544.

Olszyk, D. M., T. W. Tibbitts, and W. M. Hertzberg. 1980. Environment in open-top field chambers utilized for air pollution studies. J. Environ. Qual. 9:610-615.

Ormrod, D. P., J. C. Hale, O. B. Allen, and P. J. Laffey. 1986. Joint action of particulate fallout, nickel, and rooting medium nickel on soybean plants. Environ. Pollut. (Series A). 41:277-291.

Oshima, R. J. 1978. The impact of sulfur dioxide on vegetation: A sulfur dioxide-ozone response model. California Air Resources Board Final Report, Agreement No. A6-162-30. Sacramento.

Oshima, R. J., M. P. Poe, P. K. Braegelmann, D. W. Baldwin, and V. VanWay. 1976. Ozone dosage-crop loss function for alfalfa: A standardized method for assessing crop losses from air pollutants. J. Air Pollut. Contr. Assoc. 26:861-865.

Payer, H. D., L. W. Blank, G. Gnatz, W. Schmolke, P. Schramel, and C. Bosch. 1986. Simultaneous exposure of forest trees to various pollutants and climatic stress. Water, Air, and Soil Pollution 31:485-491.

Pfeffer, H.-U. 1982. Das Telemetrische Echtzeit-Mehrkomponenten-Ertassungs-System IEMES zur Immissionsuberwachung in Nordrhein-Westfalen, LIS-Berichte, 19, Landesanstalt fur Immissionsschutz des Landes Nordrhein-Westfalen, Essen, Federal Republic of Germany.

Piersol, J. R., and J. J. Hanan. 1975. Effect of ethylene on carnation growth. J. Amer. Soc. Hort. Sci. 100:679-681.

Posthumus, A. C. 1978. New results from SO_2-fumigations of plants. VDI-Berichte 314:225-230.

Preston, E. M., and J. J. Lee. 1982. Design and performance of a field exposure system for evaluation of the ecological effect of SO_2 on native grassland. Environ. Monit. Assess. 1:213-228.

Raynal, D. J., J. R. Roman, and W. M. Eichenlaug. 1982. Response of tree

Reagan, J. 1983. Air quality data interpretation. In: National Crop Loss Assessment Network (NCLAN) 1982 Annual Report. EPA-600/3-84-049. U.S. Environmental Protection Agency, Corvallis, Oregon. pp. 198-219.

Rebbeck, J., and E. Brennan. 1984. The effect of simulated acid rain and ozone on the yield and quality of glasshouse-grown alfalfa. Environ. Pollut. (Series A) 36:7-16.

Reich, P. B., R. G. Amundson, and J. P. Lassoie. 1982. Reduction in soybean yield after exposure to ozone and sulfur dioxide using a linear gradient exposure technique. Water, Air, Soil Pollut. 17:29-36.

Reiners, W. A., and R. K. Olson. 1984. Effects of canopy components on throughfall chemistry: An experimental analysis. Oecologia 63:320-330.

Roberts, T. M. 1981. Effects of stack emissions on agriculture and forestry. Central Electric Generating Board. Research, July:11-24. Leatherhead, United Kingdom.

Roberts, T. M., R. M. Bell, D. C. Horsman, and K. E. Colvill. 1983. The use of open-top chambers to study the effects of air pollutants, in particular sulphur dioxide, on the growth of ryegrass *Lolium perenne* L. Part I. Characteristics of modified open-top chambers used for both air-filtration and SO_2-fumigation experiments. Environ. Pollut. 31:9-33.

Rogers, H. H., H. E. Jeffries, E. P. Stahel, W. W. Heck, L. A. Ripperton, and A. M. Witherspoon. 1977. Measuring air pollutant uptake by pants: A direct kinetic technique. J. Air Pollut. Contr. Assoc. 27:1192-1197.

Runeckles, V. C., K. T. Palmer, and H. Trabelsi. 1981. Effects of field exposures to SO_2 on Douglas fir, *Agropyron spicatum*, and *Lolium perenne* Sil. Fen. 15:505-515.

Runeckles, V. C., L. M. Staley, and N. R. Bulley. 1978. A downdraft chamber for studying the effects of air pollutants on plants. Can. J. Bot. 56:768-778.

Rutter, A. J. 1975. The hydrological cycle in vegetation. In: J. C. Monteith (ed.) Vegetation and the Atmosphere. Volume I. Academic Press, New York. pp. 111-150.

Sager, J. C. 1982. Guidelines for measuring and reporting environmental parameters for plant experiments in growth chambers. Amer. Soc. Agric. Engineering Paper 82-4056. ASAE Environment of Plant Structures (SE-303) Committee. St. Joseph, Michigan.

Scherbatskoy, T., and R. M. Klein. 1983. Response of spruce and birch foliage to leaching by acidic mists. J. Environ. Qual. 12:189-195.

Sestak, Z., J. Catsky, and P. G. Jarvis. 1971. Plant Photosynthetic Production. Manual of Methods. W. Junk, The Hague.

Seufert, Von G., and U. Arnd. 1985. Open-top kammern als teil einer konzepts zur okosystemaren untersuchung der neuartigen woldschaden. Allg. Forstz. 40:13-20.

Shafer, S. R., L. F. Grand, R. I. Bruck, and A. S. Heagle. 1985. Formation of ectomycorrhizae on Pinus taeda seedlings exposed to simulated acidic rain. Can. J. For. Res. 15:66-71.

Shinn, J. H., B. R. Clegg, M. L. Stuart, and S. E. Thompson. 1976. Exposures of field-grown lettuce to geothermal air pollution -- photosynthetic and stomatal responses. J. Environ. Sci. Health (Part A) 11:603-612.

Shinn, J. H., B. R. Clegg, and M. L. Stuart. 1977. A linear-gradient chamber for exposing field plants to controlled levels of air pollutants. UCRL Reprint No. 80411. Lawrence Livermore Laboratory. University of California, Livermore.

Shinn, J. H. 1979. Problems in assessment of air pollution effects on vegetation. In: J. R. Pfaffling and E. N. Ziegler (eds.). Advances in Environmental Sciences and Engineering. Gordon and Breach Science Publishers, Inc. New York. pp. 88-105.

Shriner, D. S. 1979. Atmospheric Deposition. In: W. W. Heck, S. V. Krupa, and S. N. Linzon (eds.) Handbook of Methodology for the Assessment of Air Pollution Effects on Vegetation, Air Pollution Control Association, Pittsburgh. pp. 11-1 to 11-27.

Shriner, D. S., and J. W. Johnston. 1981. Effects of simulated, acidified rain on nodulation of leguminous plants by Rhizobium spp. Environ. Exp. Bot. 21:199-209.

Shriner, D. S., C. H. Abner, and L. K. Mann. 1977. Rainfall simulator for environmental application. Oak Ridge National Laboratory Technical Publication No. 5151. Oak Ridge National Laboratory, Tennessee. 17 pp.

Shriner, D. S., J. W. Johnson, G. E. Taylor, R. J. Luxmoore, R. K. McConathy, S. B. MaLaughlin, A. S. Heagle, R. J. Norby, B. K. Takemoto, D. T. Dubay, D. H. Abner, and D. D. Richter. 1986. Acidic deposition: Effects on agricultural crops. Final Report, Project No. 1908-02, Electric Power Research Institute, Palo Alto, California. In press.

Silberman, D. H., and D. C. McCune. 1978. Some factors affecting the response of plants to simulated cooling tower saline mist. In: Proceedings of a Symposium on Environmental Effects of Cooling Tower Emissions. WRRC Special Report N. 9, University of Maryland. pp. 1-9.

Skeffington, R. A., and T. M. Roberts. 1985. The effects of ozone and acid mist on Scots pine saplings. Oecologia 65:201-206.

Skelly, J. M., Y.-S. Yang, B. I. Chevone, S. J. Long, J.E . Nellessen, and W. E. Winner. 1984. Ozone concentrations and their influence on forest species in the Blue Ridge mountains of Virginia. In: D. D. Davis, A. A. Millen, and L. Dochinger (eds.) Symposium on Air Pollution and the Productivity of the Forest. Izaak Walton League of America, Arlington, Virginia. pp. 143-159.

Spierings, F. 1967. Method for determining the susceptibility of trees to air pollution by artificial fumigation. Atmos. Environ. 1:205-210.

Stensland, G. J. 1984. Deposition and monitoring. In: A. P. Altshuller and R. A. Linthurst (eds.) The Acidic Deposition Phenomenon and Its Effects. Critical Assessment Review Papers. Volume 1. Atmospheric Sciences. U.S. Environmental Protection Agency, Washington, D.C. EPA-600/8-83-016BF. pp. 8-1 - 8-98.

Stuanes, A. O. 1984. A simple extraction as an indicator of soils' sensitivity to acid preciptation. Acta Agric. Scand. 34:113-127.

Taylor, G. E., Jr., and D. T. Tingey. 1979. A gas-exchange system for assessing plant performance in response to environmental stress. U.S. Environmental Protection Agency, Research Triangle Park, North Carolina. EPA-600/3-79-108.

Taylor, G. E., Jr., and R. J. Norby. 1985. The significance of elevated levels of ozone on natural ecosystems of North America. In: S. D. Lee (ed.) Evaluation of the Scientific Basis for Ozone/Oxidant Standards. Air Pollution Control Association, Pittsburgh, Pennsylvania. pp. 152-176.

Temple, P. J., O. C. Taylor, and L. F. Benoit. 1985. Cotton yield responses to ozone as mediated by soil moisture and evapotranspiration. J. Environ. Qual. 14:55-60.

Thompson, C. R., and J. O. Ivie. 1965. Methods for reducing ozone and/or introducing controlled levels of hydrogen fluoride into airstreams. Int. J. Air Water Pollut. 9:799-805.

Thompson, C. R., and D. M. Olszyk. 1985. A Field Air-Exclusion System for Measuring the Effects of Air Pollutants on Crops. EPRI EA-4203. Final Report, Project 1908-3. 130 pp. Electric Power Research Institute, Palo Alto, California.

Thompson, C. R., D. M. Olszyk, G. Kats, A. Bytnerowicz, P. J. Dawson, and J. W. Wolf. 1984. Effects of O_3 or SO_2 on annual plants of the Mojave Desert. J. Air Pollut. Contr. Assoc. 34:1017-1022.

Thompson, C. R., and O. C. Taylor. 1966. Plastic covered greenhouses supply controlled atmospheres to citrus trees. Trans. Am. Soc. Agric. Eng. 9:338-339.

Thompson, C. R. and O. C. Taylor. 1969. Effects of air pollutants on growth, leaf drop, fruit drop, and yield of citrus trees. Environ. Sci. Tech. 3:934-940.

Thorne, P. G., G. M. Lovett, and W. A. Reiners. 1982. Experimental determination of droplet impaction on canopy components of balsam fir. J. Appl. Meteorol. 21:1413-1416.

Tibbitts, T. W. 1978. Monitoring. In: W. W. Heck, S. V. Krupa, and S. N. Linzon (eds.) Handbook of Methodology for the Assessment of Air Pollution Effects on Vegetation, Air Pollution Control Association, Pittsburgh. pp. 3-1 to 3-9.

Tieszen, L. L., D. A. Johnson, and M. M. Caldwell. 1974. A portable system for the measurement of photosynthesis using 14-carbon dioxide. Photosynthetica 8:151-160.

Tingey, D. T., D. Standley, and R. W. Field. 1976. Stress ethylene evolution: A measure of ozone effects on plants. Atmos. Environ. 10:969-974.

Troiano, J., and E. J. Butterfield. 1984. Effects of simulated acidic rain on retention of pesticides on leaf surfaces. Phytopathology 74:1377-1380.

Troiano, J., L. Heller, and J. S. Jacobson. 1982. Effect of added water and acidity of simulated acid rain on growth of field-grown radish. Environ. Pollut. (Series A) 29:1-11.

Troiano, J., L. Colavito, L. Heller, and D. C. McCune. 1982. Viability, vigor, and maturity of seed harvested from two soybean cultivars exposed to simulated acidic rain and photochemical oxidants. Agric. Environ. 7:275-283.

Troiano, J., L. Colavito, L. Heller, D. C. McCune, and J. S. Jacobson. 1983. Effects of acidity of simulated rain and its joint action with ambient ozone on measures of biomass and yield in soybean. Environ. Exp. Bot. 23:113-119.

U.S. Environmental Protection Agency. 1982. Section 5 Environmental concentrations and exposures. In: Air Quality Criteria for Particulate Matter and Sulfur Oxides. Volume II of III. Research Triangle Park, North Carolina. EPA-600/8-82-029b.

U.S. Environmental Protection Agency. 1984. Concentrations of ozone and other photochemical oxidants in ambient air. In: Air Quality Criteria for Ozone and Other Photochemical Oxidants. Volume II of V. Research Triangle Park, North Carolina. EPA-600/8-84-020A.

U.S. Environmental Protection Agency. 1985. Quality Assurance Handbook for Air Pollution Measurement Systems: Volume II. Ambient Air Specific Methods. Environmental Monitoring Systems Laboratory, Research Triangle Park, North Carolina. EPA-600/4-77-027a.

Unsworth, M. H., P. V. Biscoe, and V. Black. 1976. Analysis of gas exchange between plants and polluted atmospheres. In: T. A. Mansfield (ed.) Effects of Air Pollutants on Plants. Cambridge University Press, Massachusetts. pp. 5-17.

Unsworth, M. H., and T. A. Mansfield. 1980. Critical aspects of chamber design for fumigation experiments on grasses. Environ. Pollut. (Series A) 23:115-120.

Unsworth, M. H., A. S. Heagle, and W. W. Heck. 1984a. Gas exchange in open-top field chambers. I. Measurement and analysis of atmospheric resistances to gas exchange. Atmos. Environ. 18:373-380.

Unsworth, M. H., A. S. Heagle, and W. W. Heck. 1984b. Gas exchange in open-top field chambers. II. Resistances to ozone uptake by soybeans. Atmos. Environ. 18:381-385.

Van Haut, H. 1972. Test methods to improve phytocidal pollutants. Environ. Pollut. 3:123-132.

Van Voris, P. (publication date not reported). The toxic aerosol research facility at Battelle's Pacific Nrothwest Laboratories. Facility and Equipment. Battelle Pacific Nrothwest Laboratories, Richland, Washington.

Vogelmann, h. W., T. Siccama, D. Leedy, and D. C. Ovitt. 1968. Precipitation from fog moisture in the Green Mountains of Vermont. Ecology 49:1205-1207.

Waldeman, J. D., J W. Munger, D. J. Jacobs, R. C. Flagan, J. J. Morgan, and M. R.Hoggman. 1982. Chemical composition of acid fog. Science 218:677-680.

Weinsteock, L., W. J. Kender, and R. C. Musselman. 1982. microclimate within open-top air pollution chambers and its relation to grapevine physiology. J. Amer. Soc. Hort. Sci. 107:923-926.

Winner, W. E., and H. A. Mooney. 1980a. Responses of Hawaiian pants to volcanic sulfur dioxide: Stomatal behavior and foliar injury. Science 210:789-791.

Winner, W. E., and H. A. Mooney. 1980b. Ecology of SO_2 resistance: I. Effects of fumigations on gas exchange of deciduous and evergreen shrubs. Oecologia 44:290-295.

Winner, W. E., and H. A. Mooney. 1980c. Ecology of SO_2 resistance: II. Photosynthetic changes of shrubs in relation to SO_2 absorption and stomatal behavior. Oecologia 44:296-302.

Winner, W. E., and H. A. Mooney. 1980d. Ecology of SO_2 resistance: III. Metabolic changes of C_3 and C_4 Atriplex species due to SO_2 fumigations. Oecologia 46:49-54.

Winner, W. E., G. W. Koch, and H. A. Mooney. 1982. Ecology of SO_2 resistance: IV. Predicting metabolic responses of fumigated shrubs and trees. Oecologia 52:16-21.

Wisniewski, J., and J. D. Kinsman. 1982. An overview of acid rain monitoring activities in North America. Bull. Amer. Meteorol. Soc. 63:598-618.

Wood, F. A., D. B. Drummond, R. G. Wilhour, and D. D. Davis. 1973. An exposure chamber for studying the effects of air pollutants on plants. Penn. State Univ. Prog. Rep. 335. University Park, Pennsylvania. 7 pp.

Wood T., and F. H. Bormann. 1974. The effects of artificial acid mist upon the growth of *Betula alleghaniensis* Britt. Environ. Pollut. (Series A) 7:259-268.

Wood T., and F. H. Bormann. 1975. Increases in foliar leaching caused by acidification of an artificial mist. Ambio 4:169-171.